Space Charge Compensation:
Past Experience, Current Thinking and Near-Future Opportunities

Vladimir Shiltsev

Fermilab

Content

- **Past ideas and attempts**
  - **Budker's stabilized beam**
  - **Transverse SCC by octupoles at CERN**
  - **Longitudinal compensation at LANL**
  - **Novosibirsk PSR**
- **Electron lenses or columns and IOTA**
  - **SC compensation with electron lenses – idea**
  - **E-lenses in simulations – FNAL Booster, KEK PS, CERN PS**
  - **SCC with e-column - the idea**
  - **e-column/lens studies in the Tevatron**
  - **ASTA facility , IOTA Ring and SCC experiment at Fermilab**
  - **Integrable Optics for Space Charge effects suppression**
- **Summary**

Budker's Idea (1956) – SCC for electrons

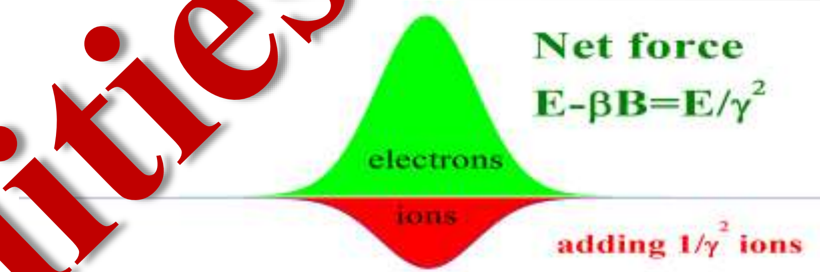
RELATIVISTIC STABILIZED ELECTRON BEAM

I. PHYSICAL PRINCIPLES AND THEORY

G. J. BUDKER

USSR Academy of Sciences, Moscow

Instabilities



CERN Symposium

ON HIGH ENERGY ACCELERATORS

AND PION PHYSICS

Geneva, 11th - 23rd June 1956

$$1 > \nu_2/\nu_1 > 1/\gamma^2$$

$$\nu = r_0 \int_0^\infty n(r)\, 2\pi r dr$$

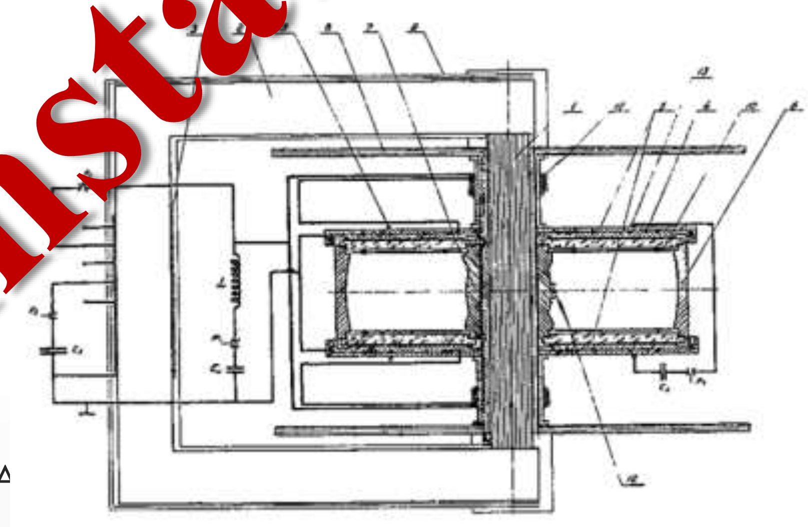


Fig. 1. Diagram of betatron set with preliminary electron accumulation.
1. Core; 2. Yoke; 3. Yoke winding; 4. Guide field winding; 5. Vaccum chamber covers; 6 and 7. Outside and inside chamber walls; 8. Shielding; 9. Yoke shielding; 10. Glass disc; 11. Back turns; 12. Electron gun; 13. Beam deflection winding.

Octupole (Multipole) Corrections at ISR

ADJUSTMENT OF THE WORKING LINES IN THE ISR

CERN ISR-MA/71-38

J.P. Gourber and K.N. Henrichsen

26 GeV/c, 30 A, mm size beams

dQ_sc~0.005   dQ_bb~0.05

Octupole field potential:

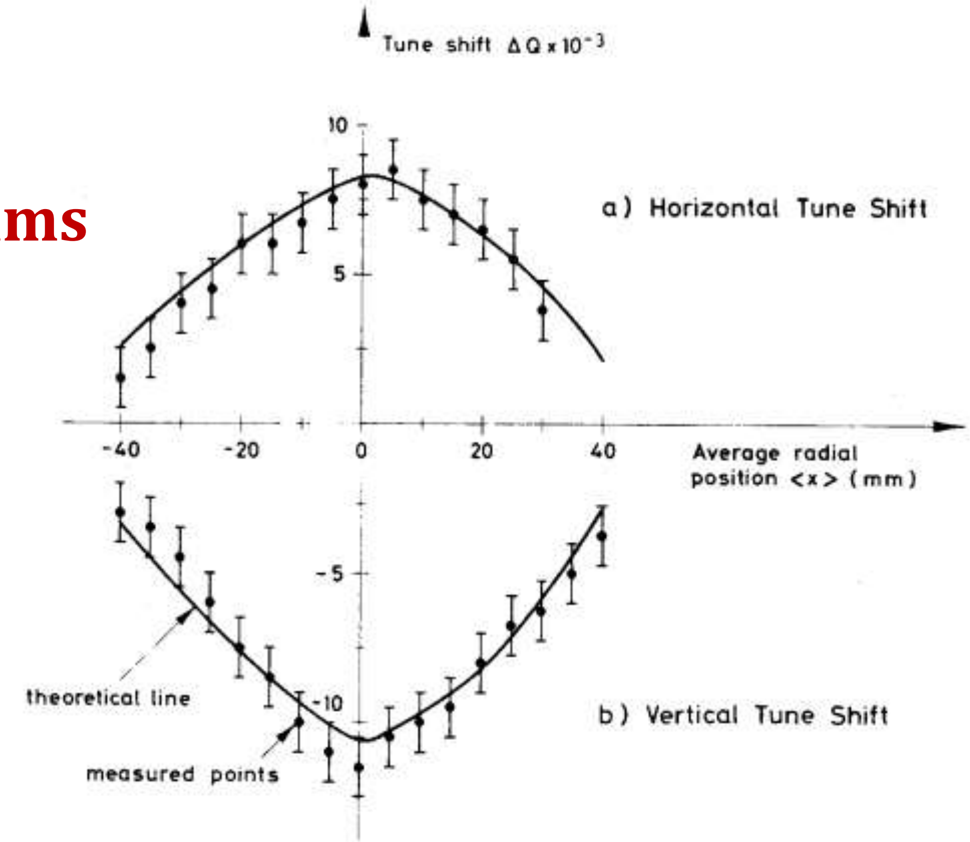
$$(x^4 - 6x^2y^2 + y^4)$$

Space Charge field:

$$(x^4 + 2x^2y^2 + y^4)$$

→ Need several families

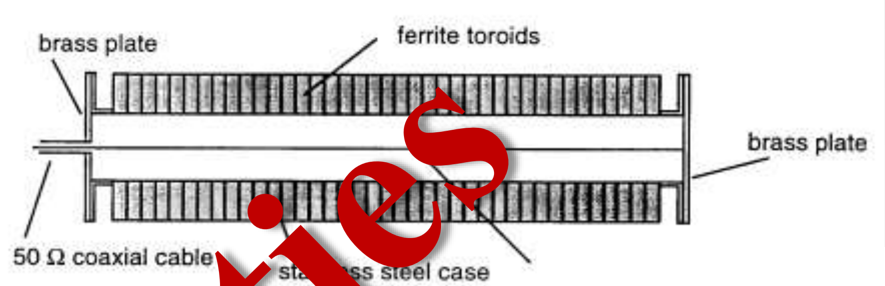
Helped to get the current



P.J. Bryant et al, CERN ISR-MA/75-54 (1975)

LANL PSR: Longitudinal SCC

$$V_s = \frac{\partial \lambda(s)}{\partial s} \left[\frac{g_0 Z_0}{2\beta\gamma^2} - \omega_0 L \right] e\beta c R$$



Z/n ~200 Ohm

Instabilities

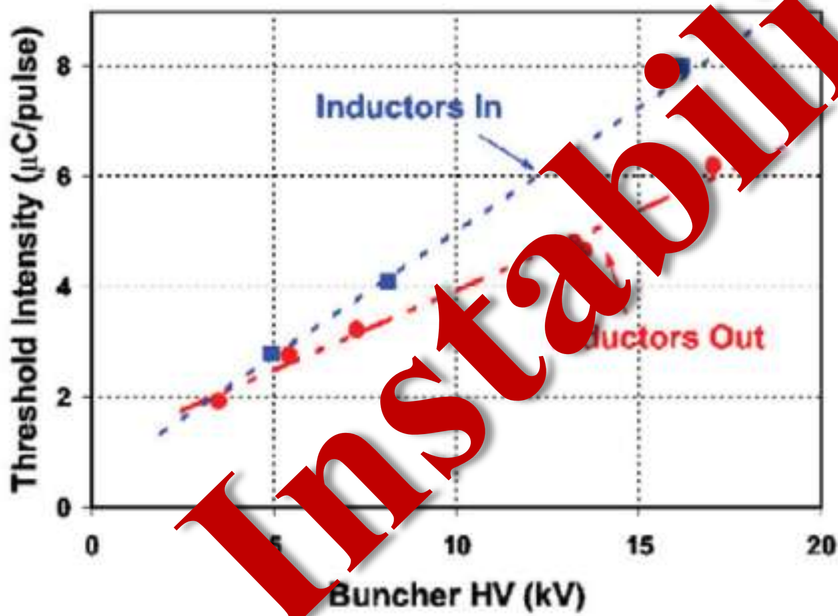
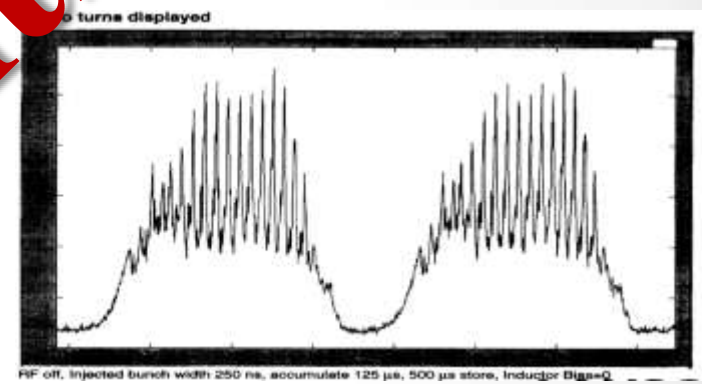
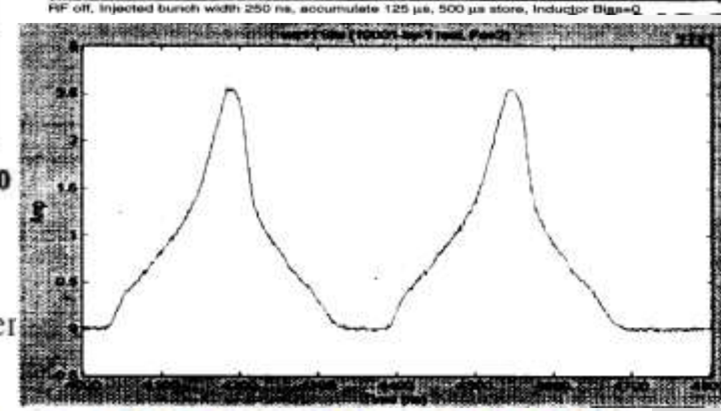


Figure 1: PSR e-p instability threshold vs rf buncher voltage with and without the inductive inserts.





M.A. Plum et al, PRST-AB 2, 064201 (1999)

Novosibisrk PSR – x10 SC limit!

Particle Accelerators
1984 Vol. 14 pp. 155-184
0031-2460/84/1403/0155$18.50/0

1984

COMPENSATED PROTON-BEAM PRODUCTION IN AN ACCELERATING RING AT A CURRENT ABOVE THE SPACE-CHARGE LIMIT

G. I. DIMOV and V. E. CHUPRIYANOV
Institute of Nuclear Physics, 630090, Novosibirsk 90, USSR

(Received April 20, 1983)

Results of experiments on the storing of intense proton beams in an accelerating ring by the charge-exchange method are presented. Compensation of the proton space charge allows proton-beam production in the ring with a current one order of magnitude higher than the space-charge limit. Studies have been made of the conditions for stabilization of the beam-beam instability, which is the major obstacle to the production of intense compensated proton beams.

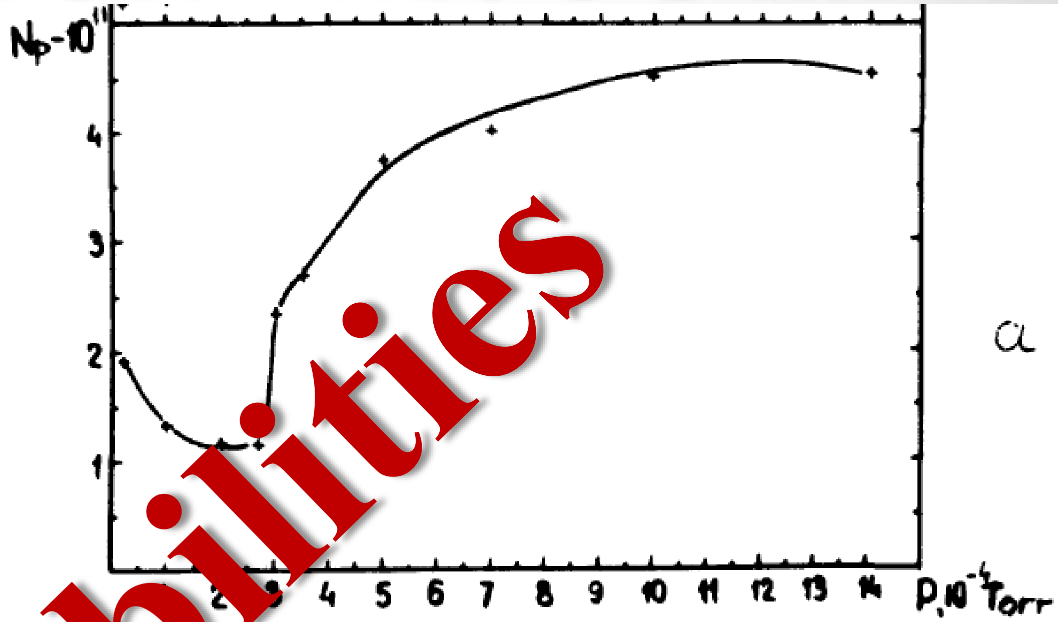


FIGURE The dependences on nitrogen pressure in the storage ring: a — the number of stored protons

1 MeV p

6.7 m

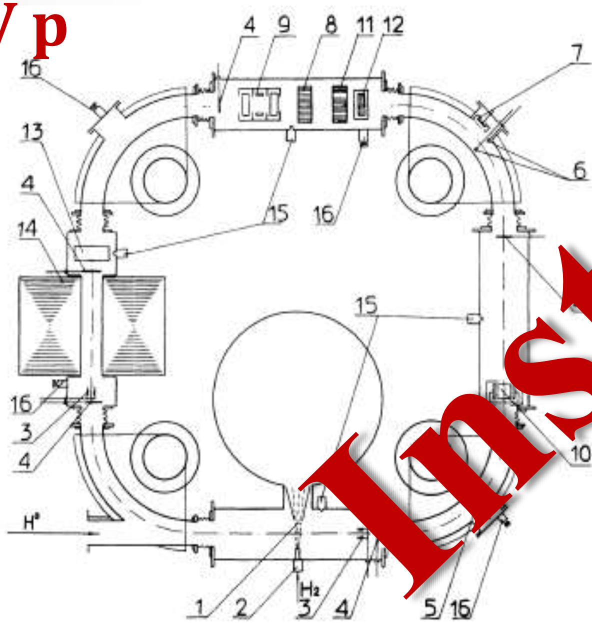


FIGURE 1 Layout of the proton storage ring. 1—secondary stripping gas target, 2—pulsed gas valve, 3—Faraday cups, 4—quartz screens, 5, 6—mobile targets, 7—ion collector, 8—Rogovsky coil, 9—"pick-up" station, 10—electrostatic transducer of quadrupole beam oscillations, 11—magneto-inductance transducer, 12—transducer of vertical beam losses with high time resolution, 13—device for measuring the secondary charged-particle concentration in the beam region, 14—betatron core, 15—electromagnetic gas valves of the system of pulsed gas leak-in, 16—microleaks of the system of stationary gas leak-in.

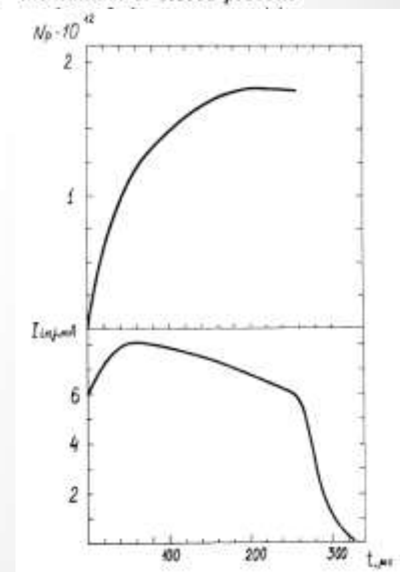
Instabilities

Gases H2, He, N2, Ar

Upto few mTorr

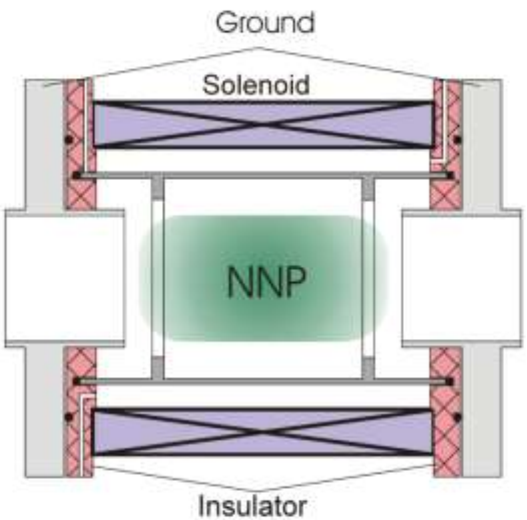
2e12 protons (w H2) = (6-9) x SC limit

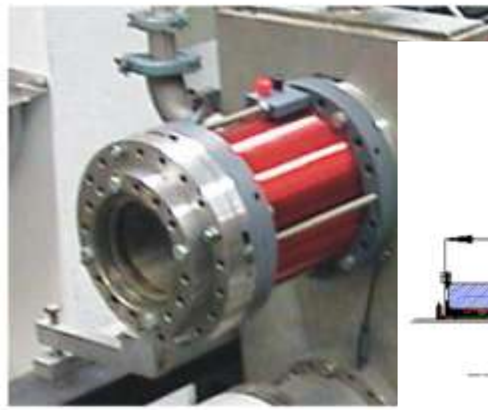
~few 100's turns



It works "one-pass" (beamlines)

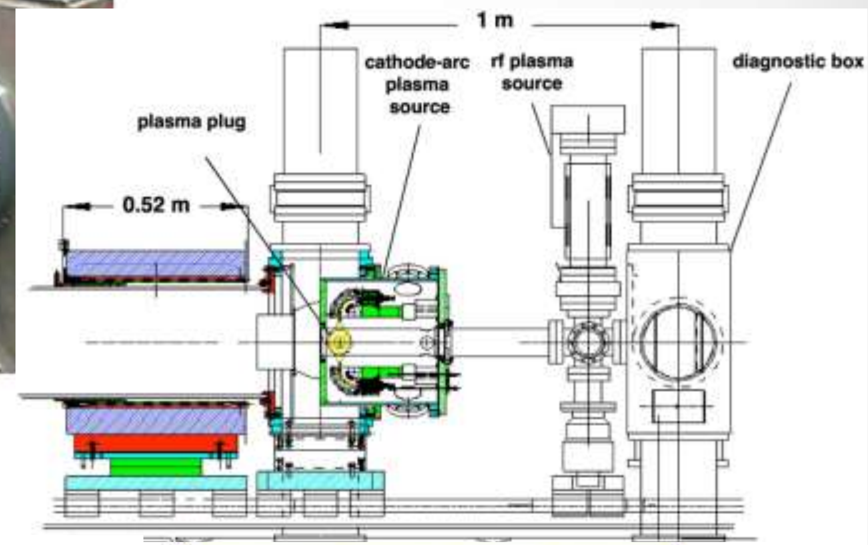
Gabor lens (1947)





NTX test (LBNL, 2000's)

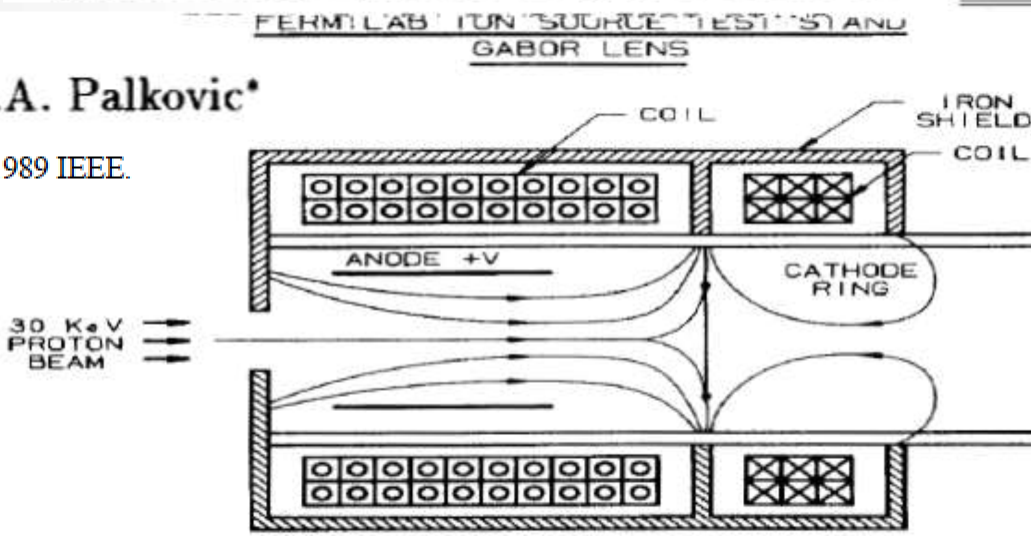
0.4-1 MeV K+ , ~0.6A

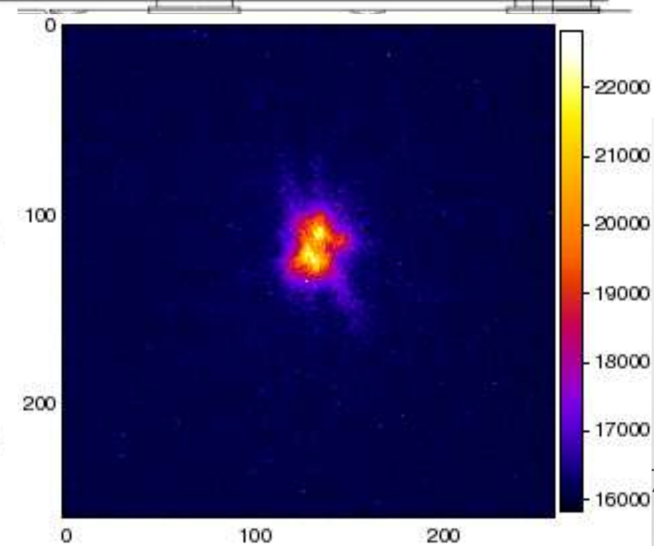


GABOR LENS FOCUSING

J.A. Palkovic*

1989 IEEE.

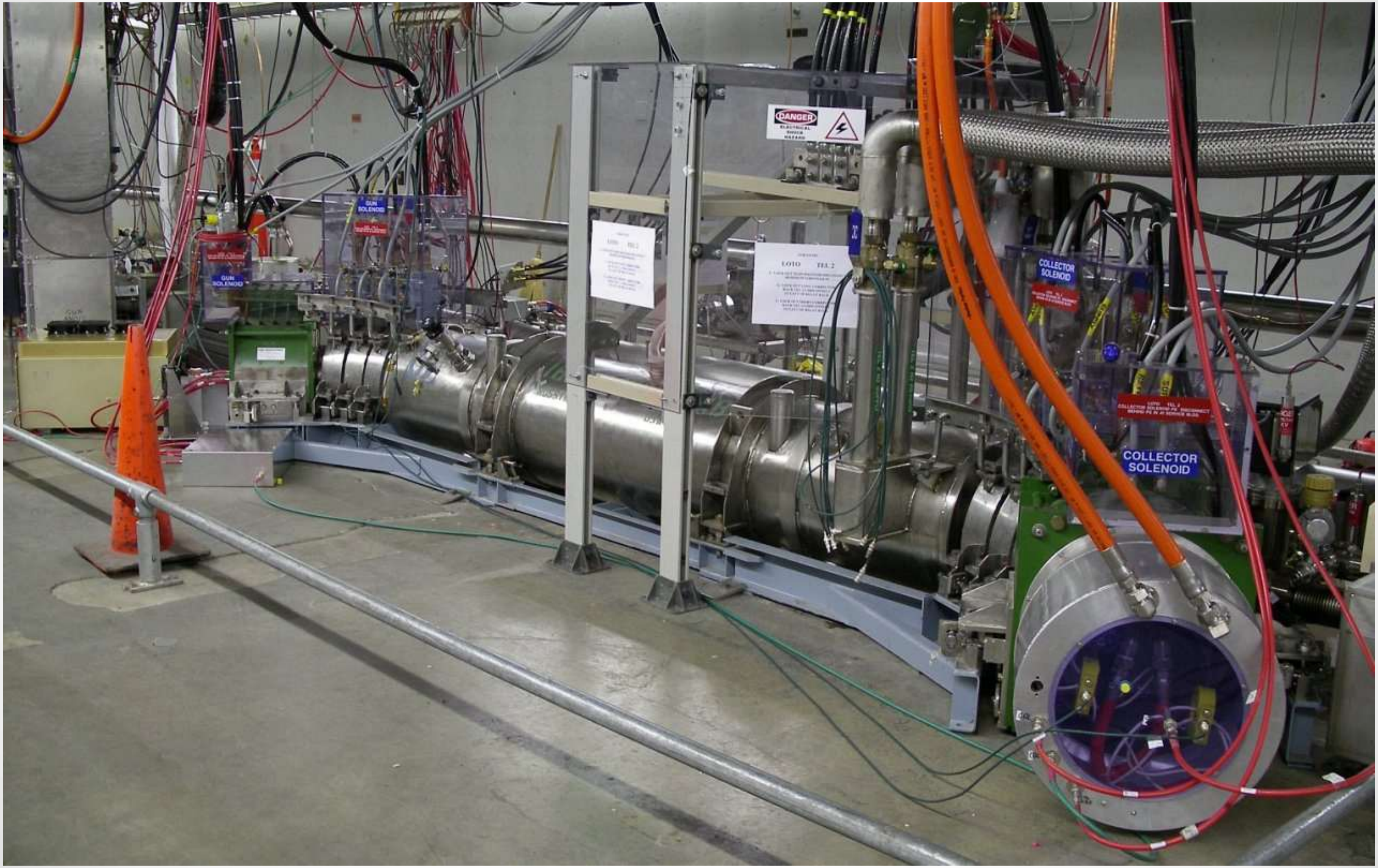




New Millenium – New Ideas

- **Electron lenses for SC compensation (2000)**
  - **Similar to e-lens for beam-beam compensation**
- **Electron columns for SCC (2007)**
- **In both cases, potential advantages:**
  - **Better control of e-charge distribution**
  - **Better stability due to strong longitudinal magnetic field that suppresses electron motion and, thus, *e-p* modes**

TEL in the Tevatron Tunnel



Electron Charge Distribution

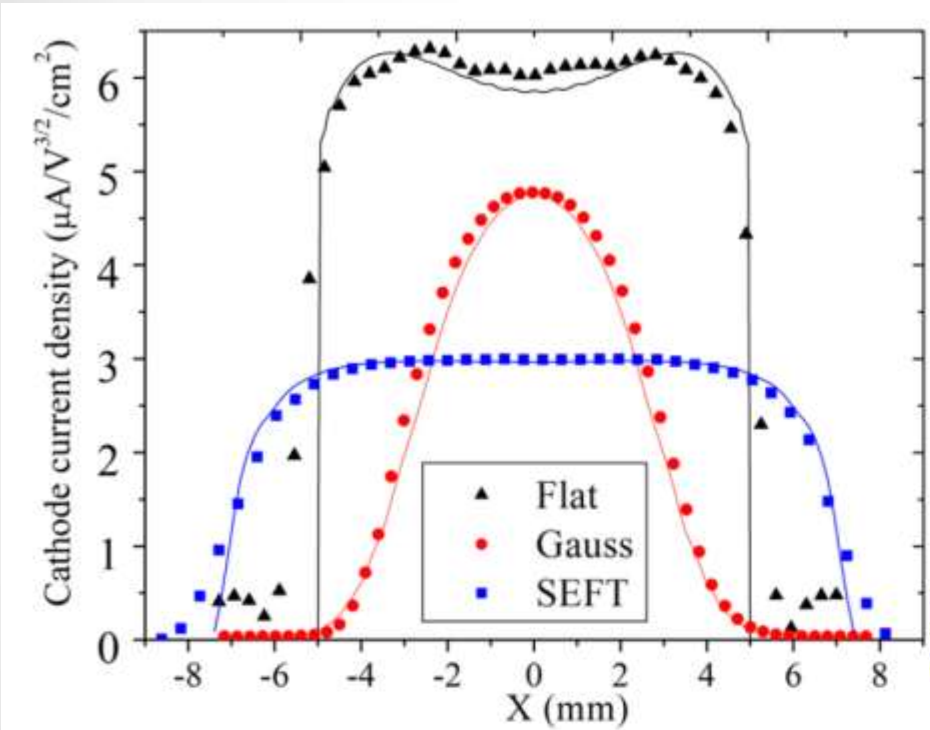


Figure 2. Three profiles of the electron current density at the electron gun cathode: black, flattop profile; red, Gaussian profile; blue, SEFT profile. Symbols represent the measured data and the solid lines are simulation results. All data refer to an anode–cathode voltage of 10 kV.

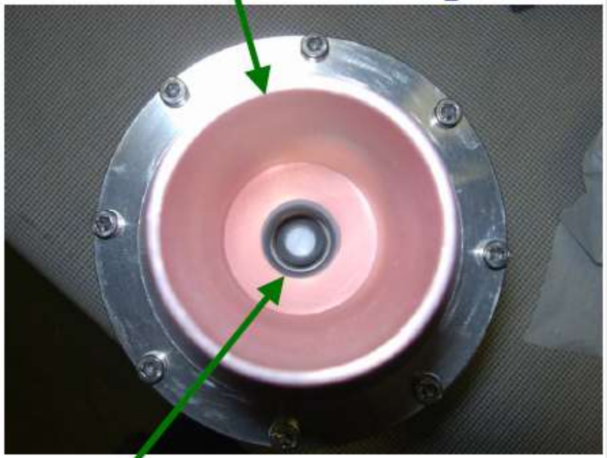
Shiltsev et al., *PRL* 99, 244801 (2007).
Shiltsev et al., NJP 10, 043042 (2008).

Electron gun

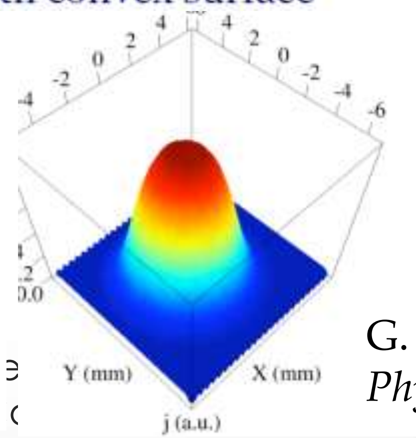
Copper anode

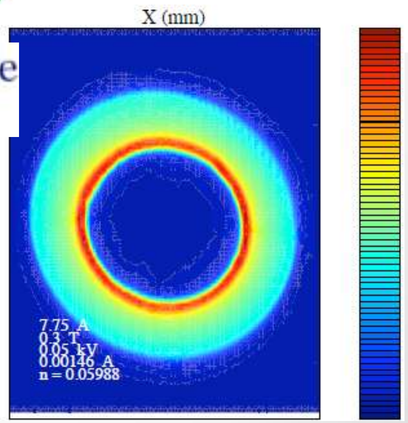
side view

top view



Tungsten dispenser cathode with convex surface



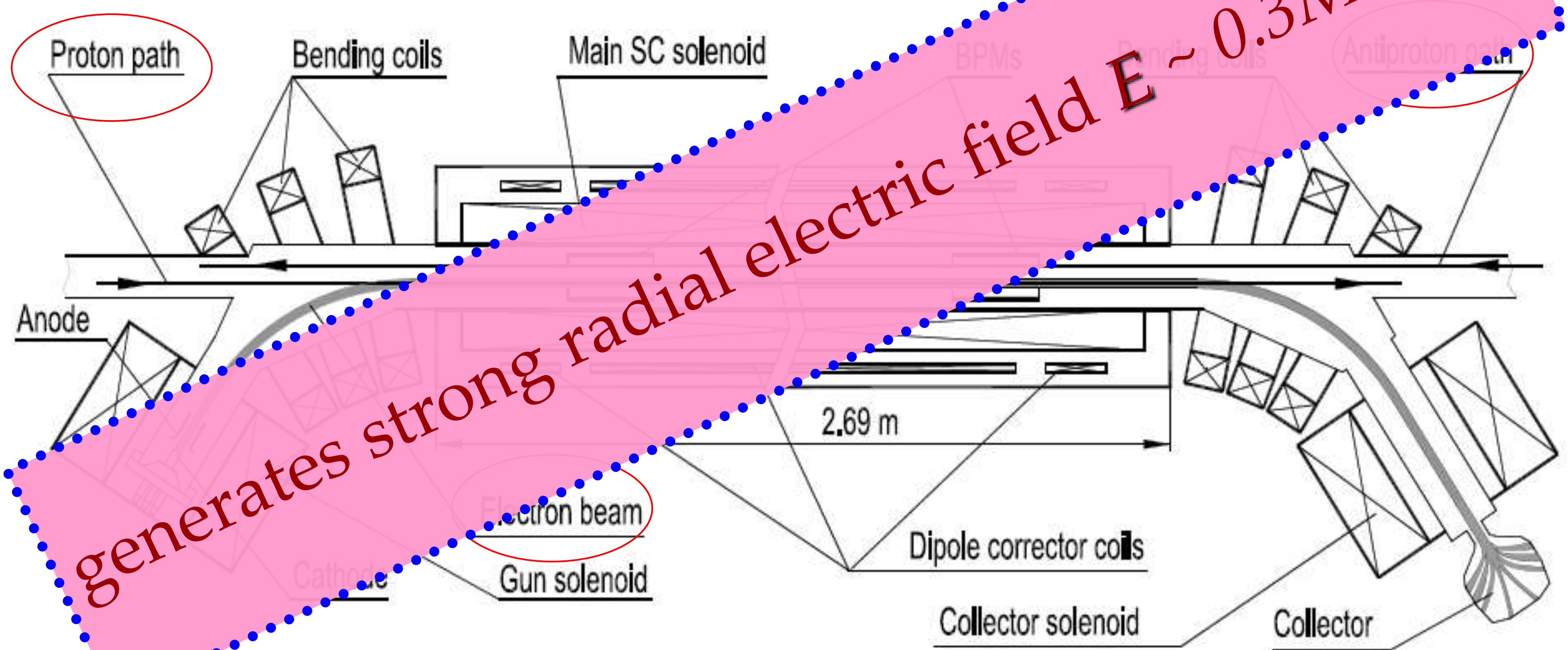


G. *Stancari*, et al., (2011)
Phys. Rev. Lett. 107, 084802

Some Facts on Electron Lenses

~4 mm dia 2 m long very straight beam of ~10kV

~1A electrons (~10^12) immersed in 3T solenoid

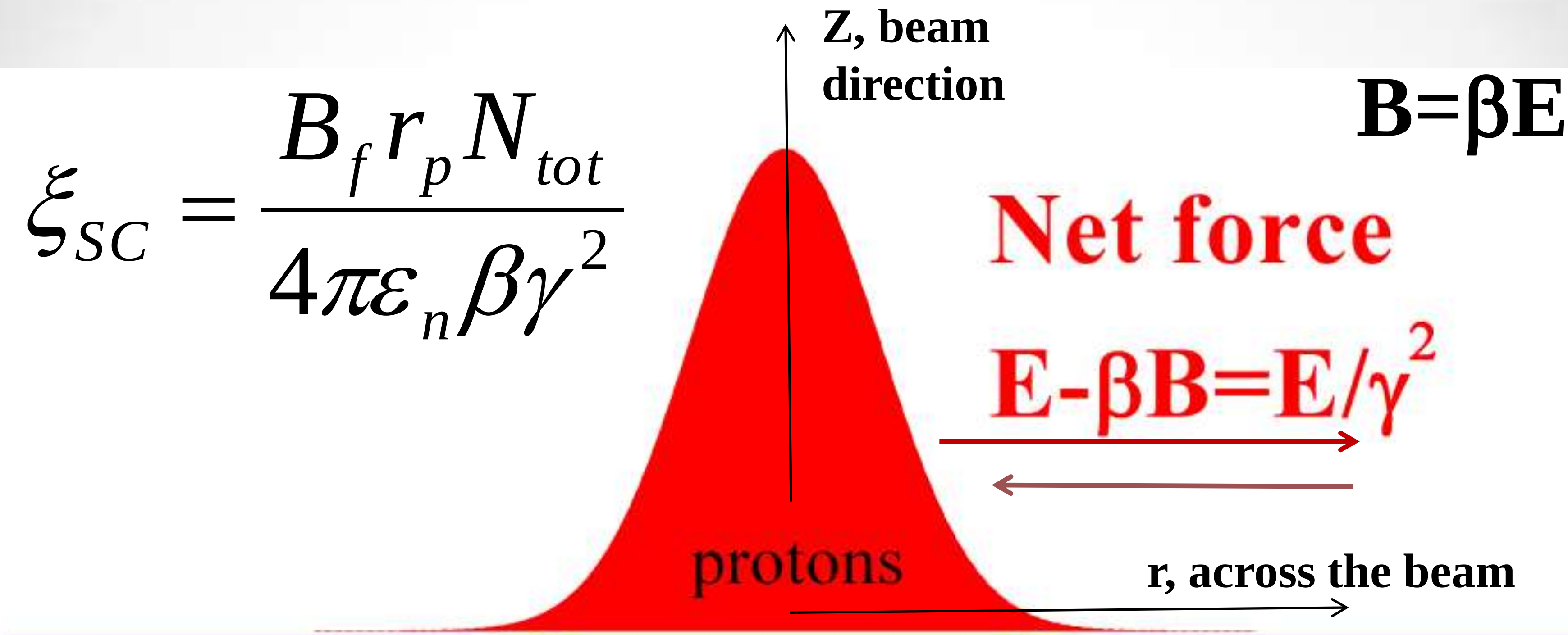


generates strong radial electric field $E \sim 0.3MV/m$

Space Charge Forces & Compensation

$$\xi_{SC} = \frac{B_f r_p N_{tot}}{4\pi\varepsilon_n \beta\gamma^2}$$

B=βE



A. Burov, G. Foster, V. Shiltsev, FNAL-TM-2125 (2000)

SCC with e-Lenses/e-Columns

- **Instead of uniformly distributing electrons around the ring with low concentration :**

$$\eta = \frac{n_e}{n_p} = \frac{1}{\gamma^2}$$

- **Electron columns will generate HIGH concentration of electrons but over a small fraction of ring circumference:**

$$f = \frac{N_{EC} L_{EC}}{C} = \frac{\eta}{\gamma^2}$$

First Example: SCC in 8 GeV Booster

2000

Fermilab FERMILAB-TM-2125 September 2000

Space-Charge Compensation in High-Intensity Proton Rings

A.V. Burov, G.W. Foster, V.D. Shiltsev
Fermi National Accelerator Laboratory
P.O. Box 500, Batavia, Illinois 60510

$$J_e = J_p B_f \frac{C}{L} \frac{\beta_e}{\gamma_p^2 \beta_p^2 (1 - \beta_e \beta_p)},$$

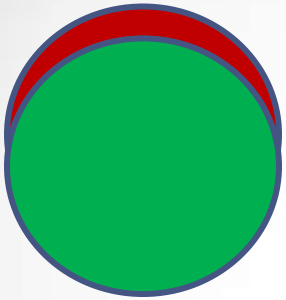
	Emittance Upgrade	Double Intensity
maximum e-current J_e, A	12.7	25.4
e-beam length	3 lenses, each L =4 m long	3 lenses, each L =4 m long
rms e-beam size, σ_e, mm	4.5	8
cathode radius, mm	12	20
B-field in gun/main solenoid, kG	3/11	4/13
e-beam energy U_e, kV	80kV	80 kV
anode-cathode voltage U_a, kV	26	41
HV RF modulator power, kW	20	50

- **To study: coherent modes and emittance growth**

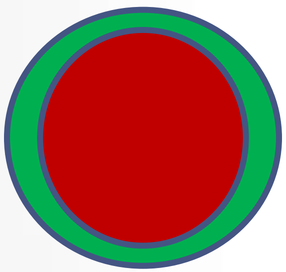
FERMILAB-TM-2125 September 2000

Coherent Modes

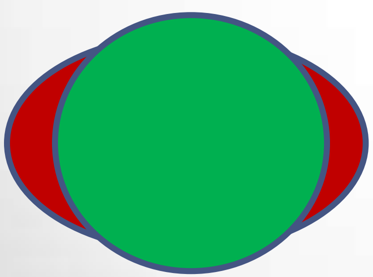
Parameter	KEK-B	FNAL-B	ISIS	AGS	AGS-B	CERN PS	CERN PS-2
ν_x/ν_y	2.17 / 2.3	6.7 / 6.8	3.7 / 4.2	8.75 / 8.75	4.8 /4.9	6.22 / 6.22	6.22 / 6.28
$\Delta\nu_{\text{exp}}$	0.23	0.4	0.4	0.58	0.5	0.27	0.36
$\Delta\nu_{\text{inc}}$	0.17	0.2	0.2	0.25	0.3	0.22	0.22
$\Delta\nu_{\text{coh}}$	0.27 / 0.08	0.36 / 0.08	0.32	0.33	0.07 / 0.2	0.27	0.33



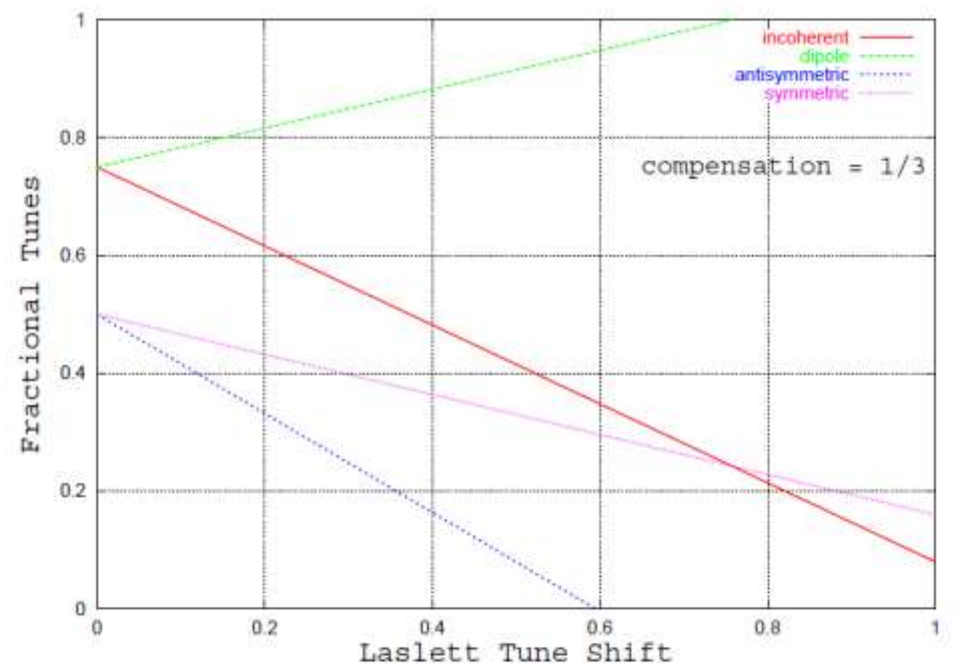
- **dipole**



- **symmetric**



- **asymmetric**



- **Is that a real concern? – need computer modeling**
- **Even if yes – dipole FB may help**

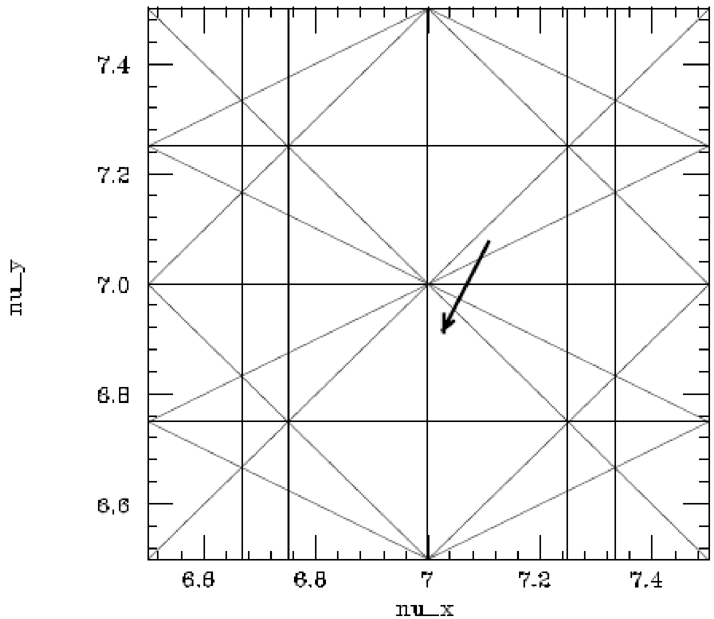
Simulations :KEK PS (S.Machida, 2001)

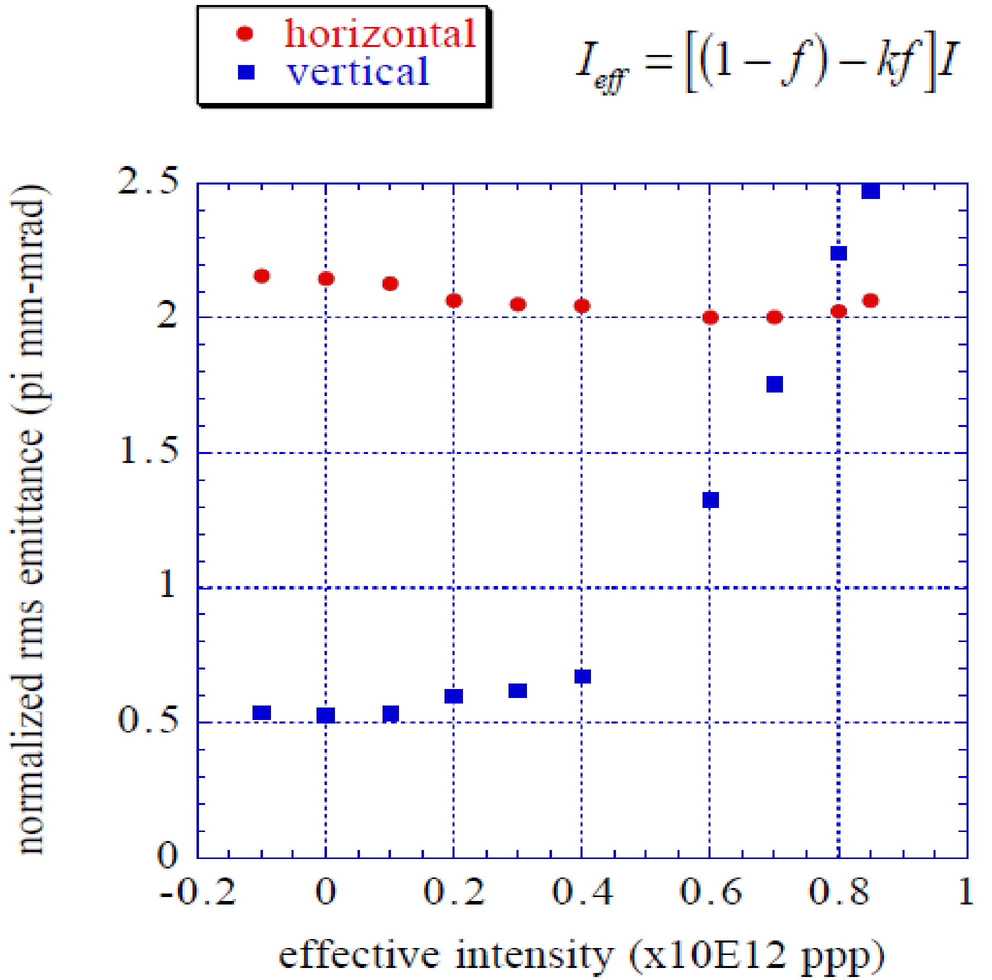
KEK PS:

500 MeV, 340 m

N_p~1e12

dQ_sc=-0.2





- **"space charge compensation with e-lenses works"**
  - **+0.1-0.2 sigma e-p displacement tolerable**

Simulations : FNAL Booster (Yu.Alexahin & V.Kapin, 2007)

Booster:

400 MeV, 474 m

P=24

N_p~4.5e12

dQ_sc=-0.3

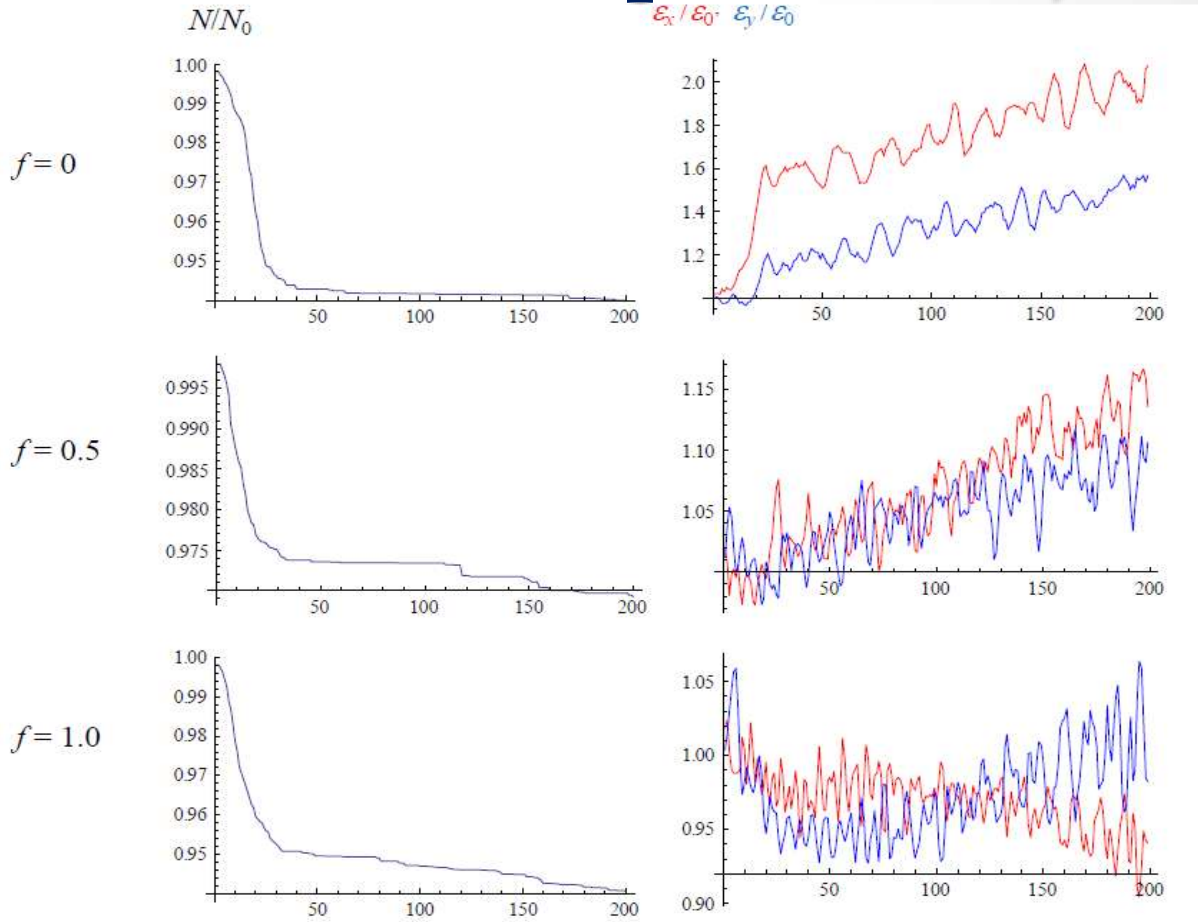
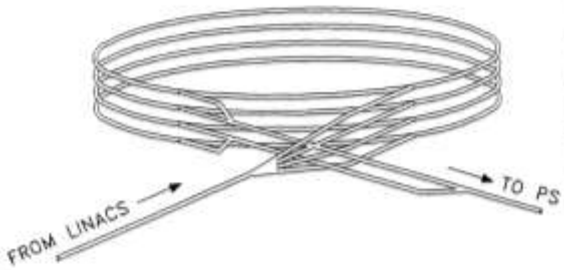


Figure 2. Normalized beam intensity and emittances vs turn number at $N_b = 6 \cdot 10^{10}$, $n_{columns}$=24 and indicated values of the compensation factor f.

- **"space charge compensation with e-lenses works"**
- **More compensators the better (24→12→3 minimum)**

Simulations: CERN PS-B (M.Aiba,2007)

THPAN074 Proceedings of PAC07, Albuquerque, New Mexico, USA



PS Booster:

50 MeV, 157 m

P=16

dQ_sc ~ -0.5

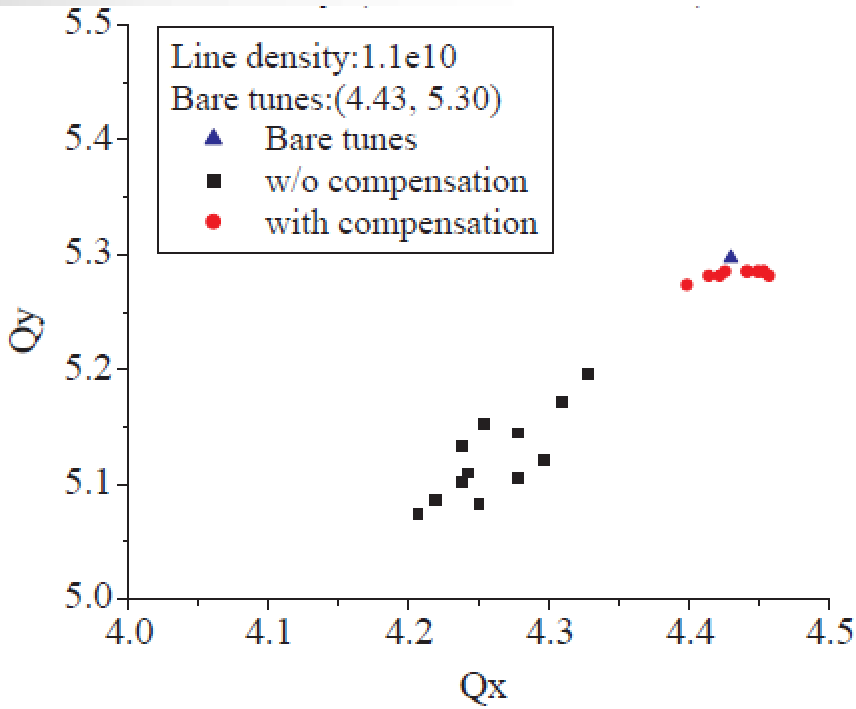
Table 1: Parameters of the CERN PS and the PS Booster (PSB) proton beams corresponding to the "ultimate" LHC.

variable	symbol	PSB	PS
kin. energy	$E_{\rm kin}$	50 MeV	1.4 GeV
circumference	C	157 m	628 m
protons/bunch	N_b	2.5×10^{12}	2.5×10^{12}
protons/beam	N_t	2.5×10^{12}	1.5×10^{13}
tr. n. emittance	$\beta\gamma\epsilon$	2.5 μm	3 μm
full bunch length	l_b/c	750 ns	180 ns
harmonic number	h	1 (&2)	7
av. beta function	$\beta_{x,y}$	5 m	15 m
superperiodicity	P	16	10
betatron tunes	$Q_{x,y}$	4.29, 5.45	6.12, 6.24
revolution period	T_0	1.7 μs	2.3 μs
bunching factor	B_f	2.2	3.4
s.c. tune shift	ΔQ^{SC}	0.76	0.35

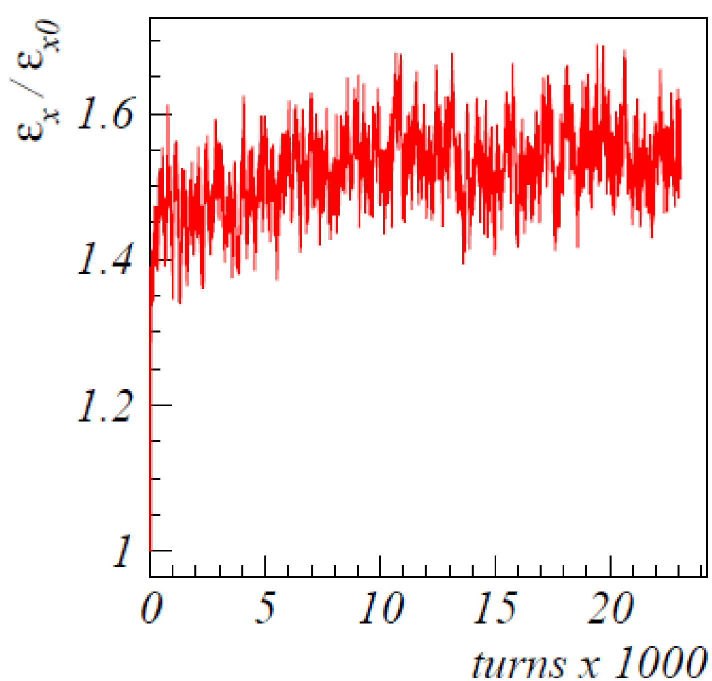
Need to increrasee for LHC ultimate intensity →

Simulations: CERN PS-B (M.Aiba,2007)

moderate beam intensity (~1/2 the nominal)



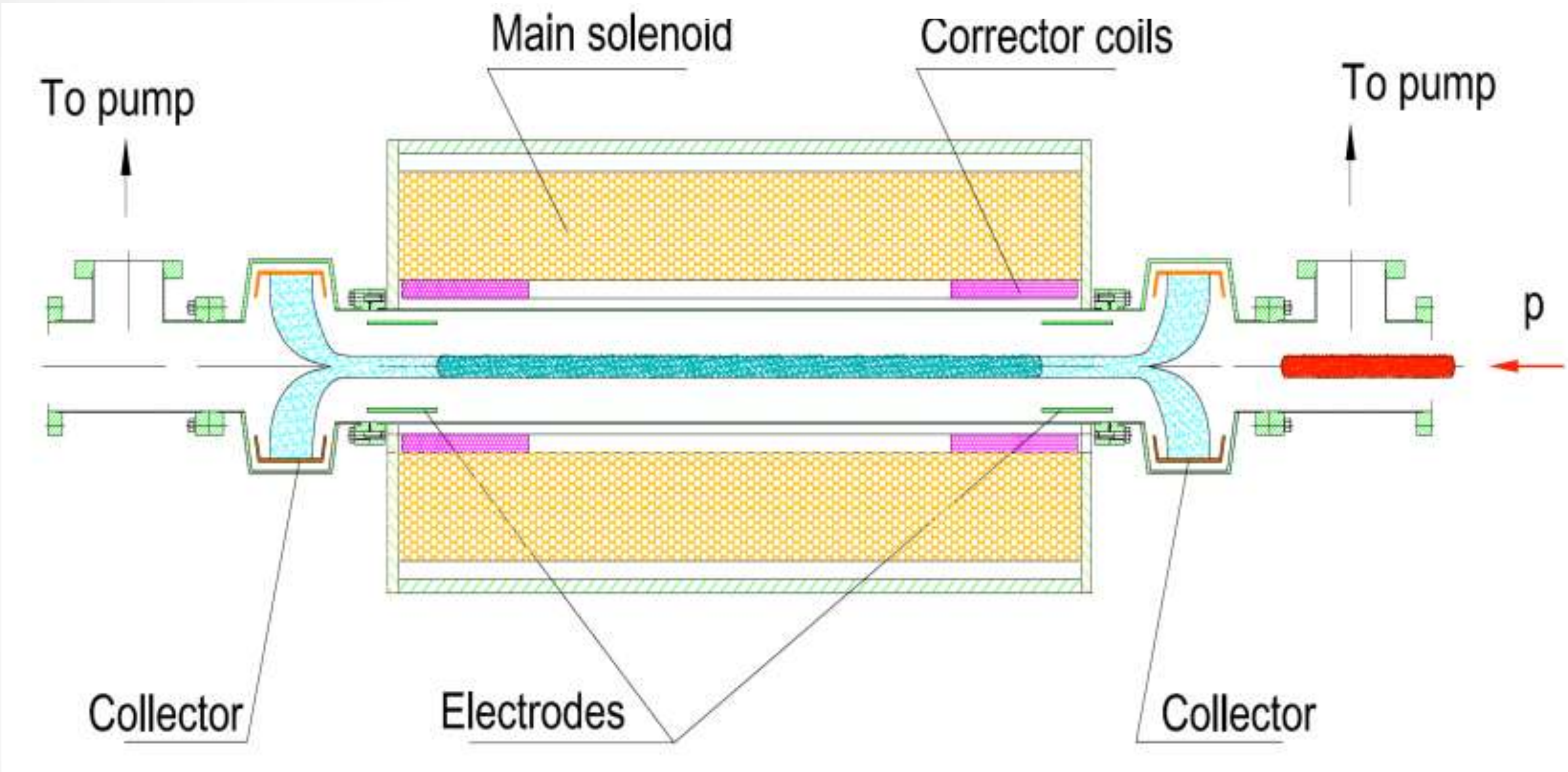
$Q_{x0} = 6.2 \quad Q_{y0} = 6.2 \quad \Delta Q = 0.1$



- **"space charge compensation with e-lenses works in principle… desrves further studies"**
  - **No evidence for coherent modes limitation in PSB and PS**
    - **Concern of overcompensation in the head and tail**
    - **More compensators the better (8 is better than 4)**

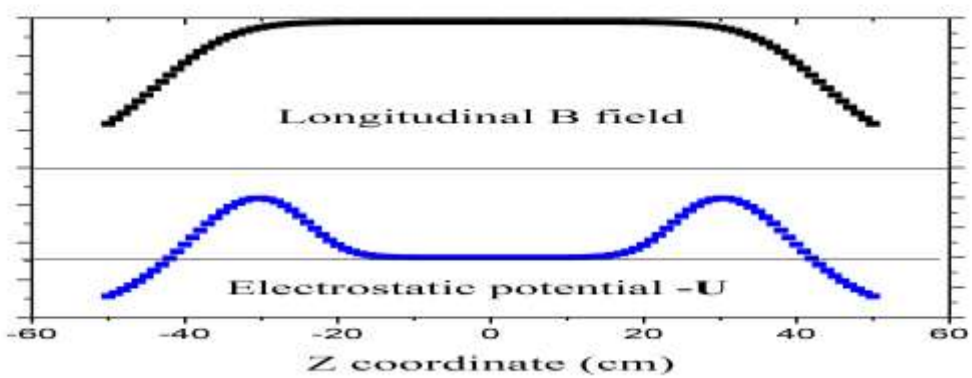
Electron Columns (2007)

V.Shiltsev, Fermilab, Batavia, IL, USA Proceedings of PAC07, Albuquerque, New Mexico, USA TUPMN106

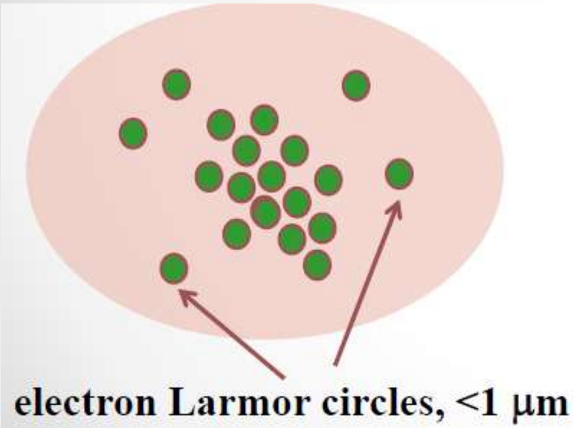


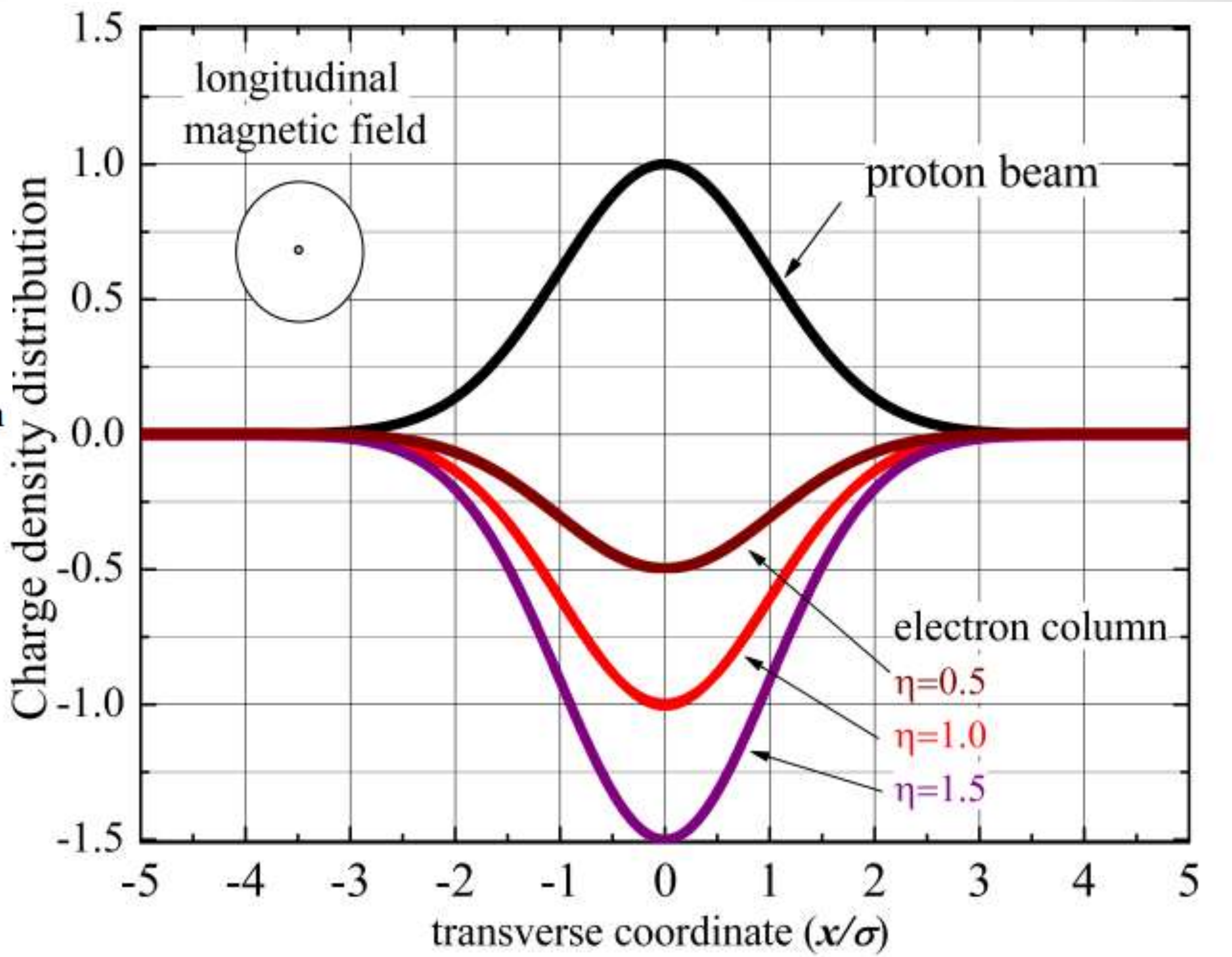
Collect ionization electrons +

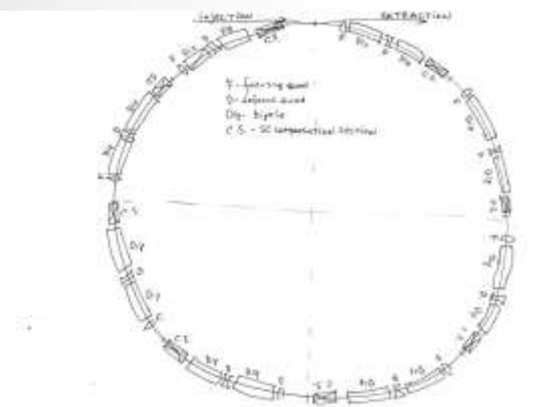
let ions escape



How high local η could be?

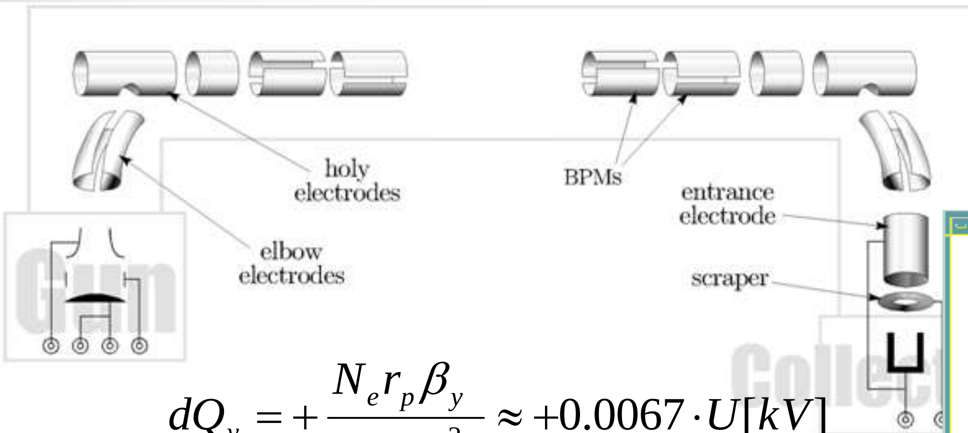






Overcompensation $\eta > 1$ possible at high field B

Electron Column studies: Tevatron with TELs (2009)



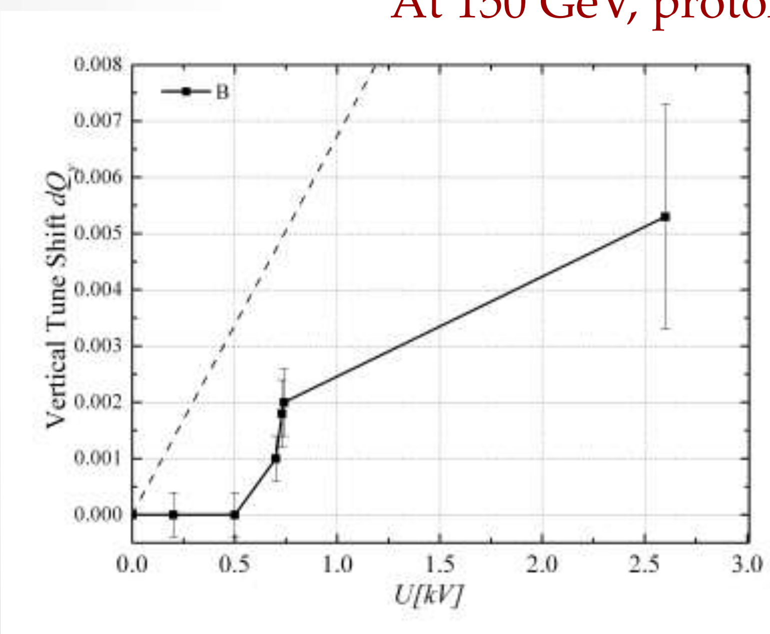
Proceedings of PAC09, Vancouver, BC, Canada TH5PFP020

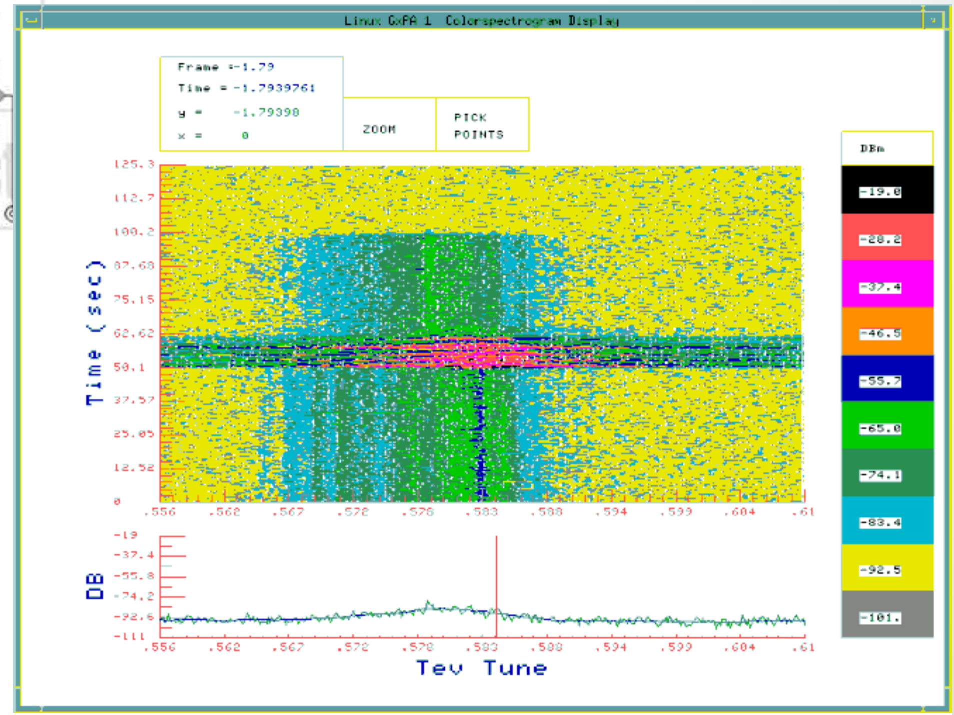
BEAM STUDIES WITH ELECTRON COLUMNS *

V. Shiltsev#, A.Valishev, G.Kuznetsov, FNAL, Batavia, IL 60510, U.S.A.
V.Kamerdzhiev, FZ-Juelich, IKP, Germany, A.Romanov, BINP, Novosibirsk, Russia

$$dQ_y = +\frac{N_e r_p \beta_y}{4\pi\gamma\sigma^2} \approx +0.0067 \cdot U[kV]$$

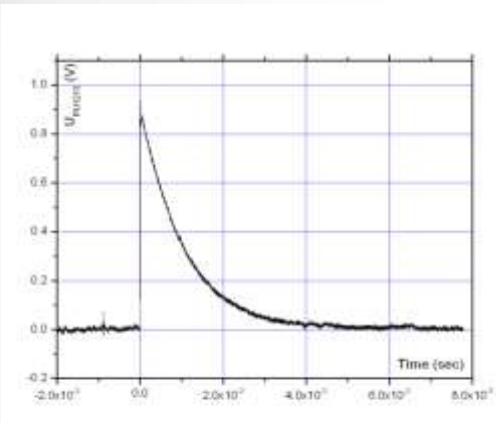
At 150 GeV, protons

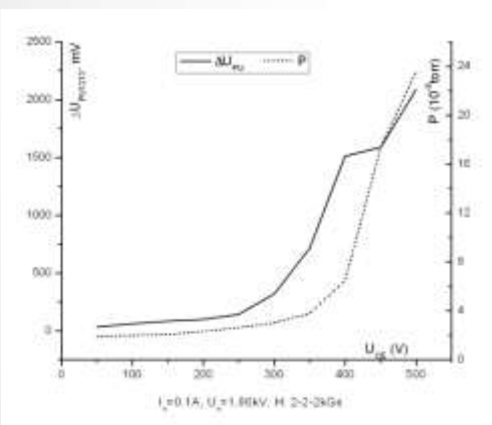


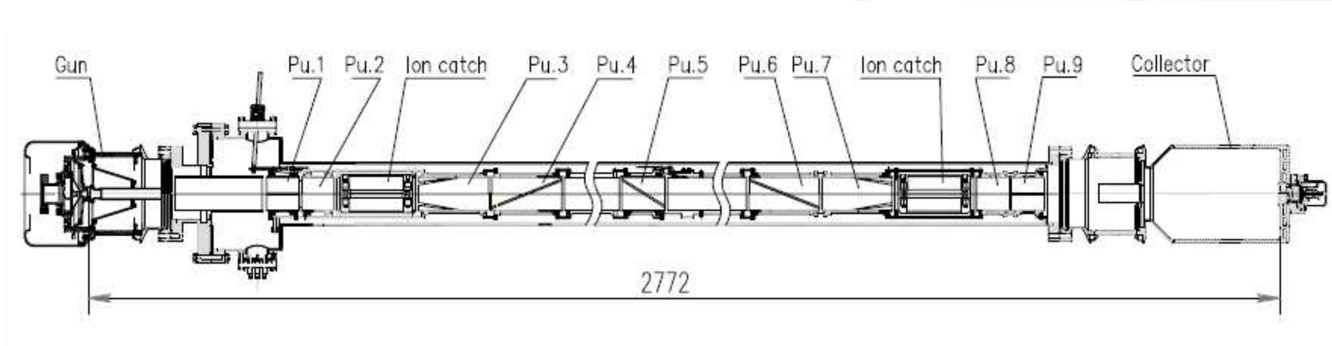


Observed tune shift, vacuum activity and instability → need to understand dynamics of ionization electrons

Electron Column studies: 10 kV e-Bench Test area (2009)





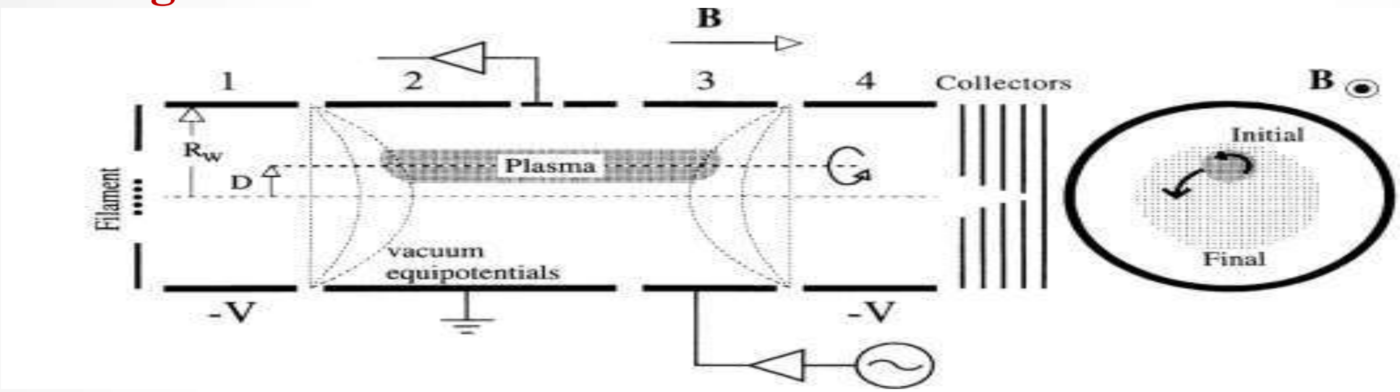


- **Observed charge accumulation**
- **Plasma oscillations**

Complex Dynamics of Non-neutral magnetized Plasmas

"Rotating Wall" E-field

C.Surko, A.Kabantsev (UCSD), J.Fajans (USB),



***In the case of fast transiting ions the growth rate of diocotron modes is relatively small and drops strongly with *B*

*** In the case of slow trapped ions the growth rate of diocotron modes is defined by the neutralization (space-charge compensation) level solely, and thus may be very dangerous

*** There are various stabilization and damping techniques, out of which the most effective has to be chosen according to plasma and trap parameters

*** Rotating wall technique might be used to compensate the radial transpor caused by the mode damping processes

Issues to Explore in (Theory then) Experiment

1. **Stability of the system (transverse motion)**
2. **(Dynamic) matching of transverse p-charge distribution**
3. **Appropriate longitudinal compensation (for not-flat proton bunches)**
4. **Electron lenses vs electron columns**
5. **Practical implementation (in existing facilities)**

= the Need of Experimental Study at a dedicated AARD facility → *ASTA*

Advanced Superconducting Test Accelerator (ASTA)

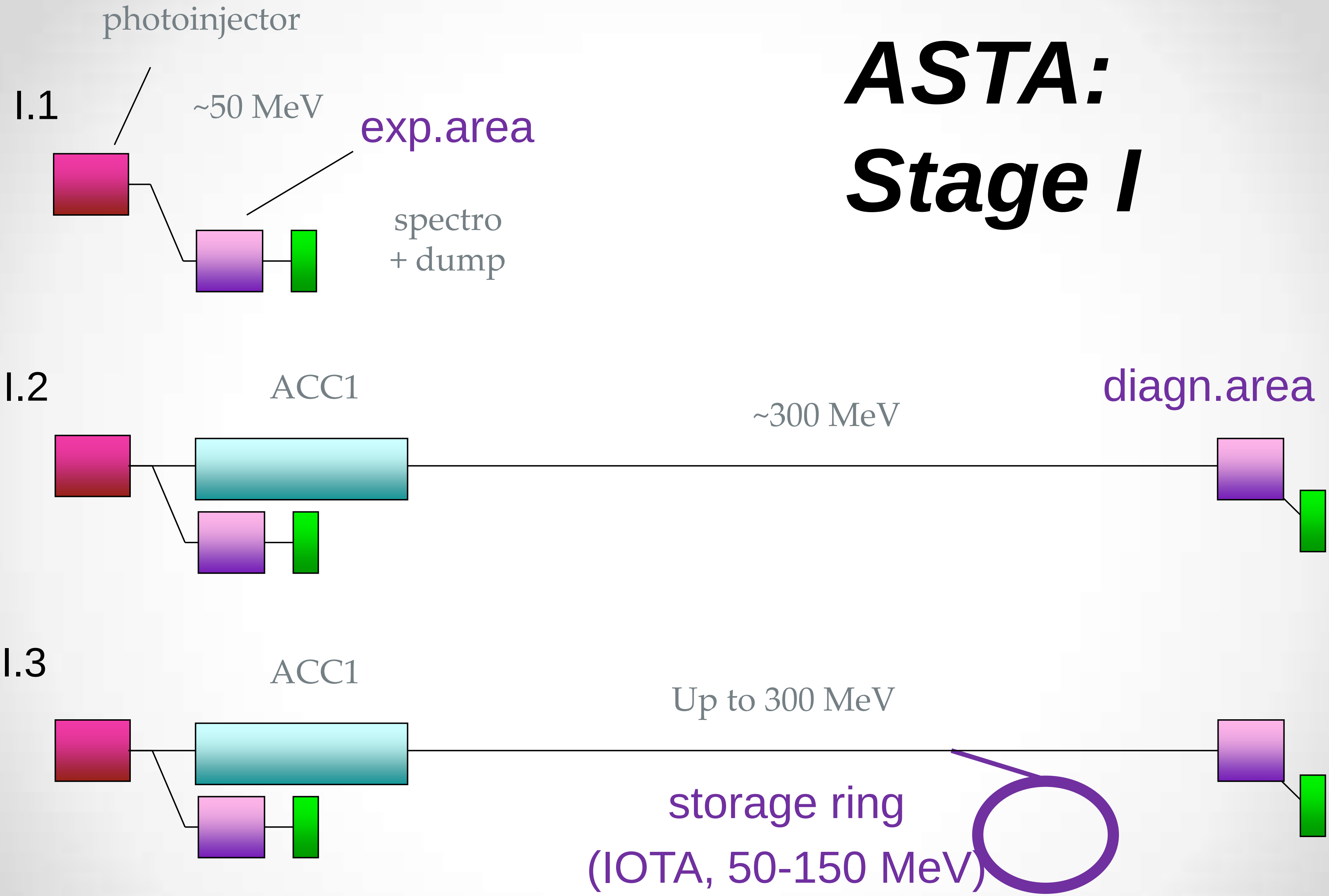
Expansion Building for Accelerator R&D at ASTA

Digging Tunnel

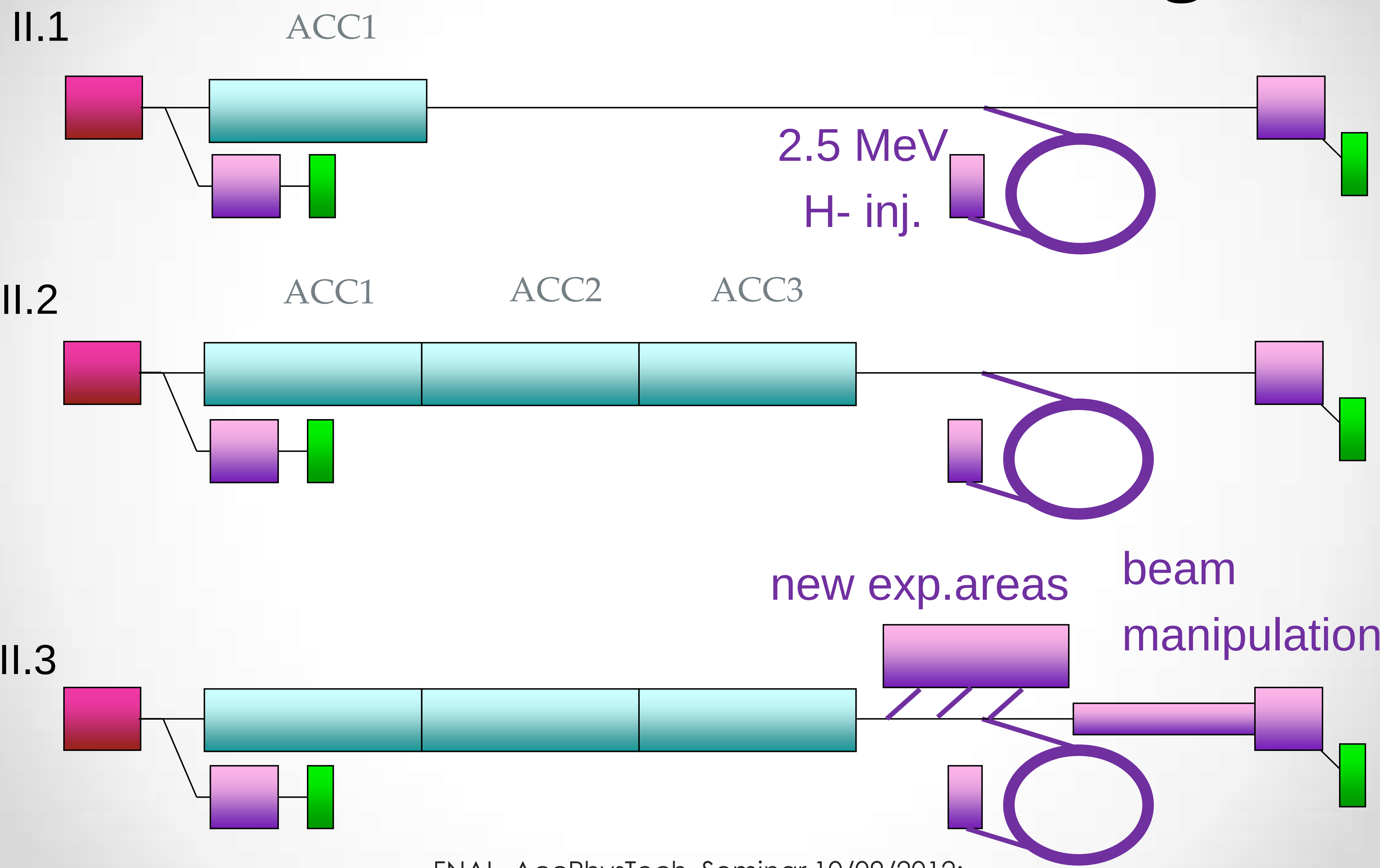
Finished Tunnel

Electrical Service Building

ASTA: Stage I


photoinjector
I.1
~50 MeV
exp.area
spectro
+ dump
I.2
ACC1
~300 MeV
diagn.area
I.3
ACC1
Up to 300 MeV
storage ring
(IOTA, 50-150 MeV)

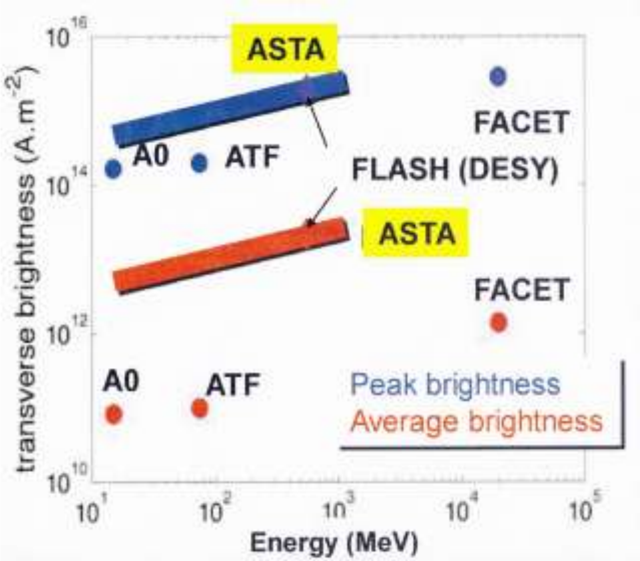
ASTA: Stage II



ASTA : Uniqueness

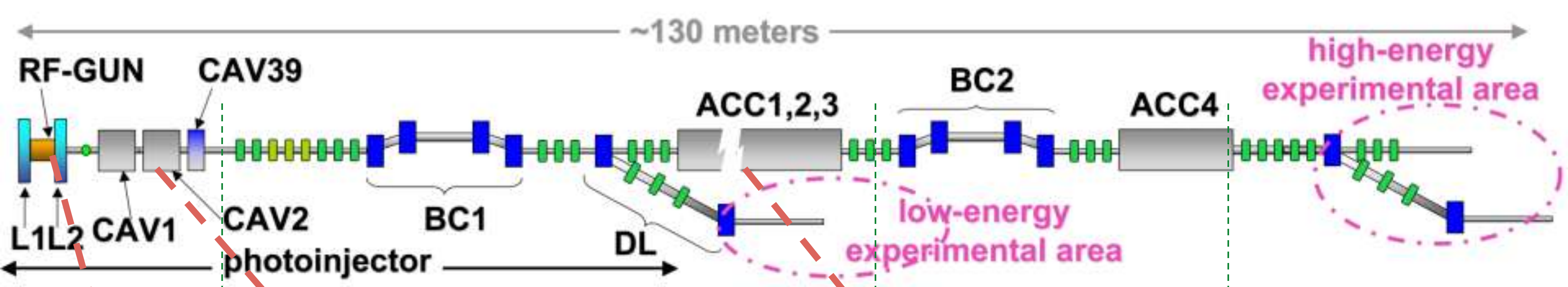
Facility for Intensity Frontier accelerator R&D & SRF development – the only in the US & World

Facility	Main beams	HEP Discovery Science		Applications
		Intensity Frontier	Energy Frontier	
ATF (BNL)	e-, CO_2 laser		PWFA, LPWA for e+e- LCs	FEL, γ's, medical laser-gas
A0 (FNAL)	e-		e+e- LCs, PWFA	FEL
AWA (ANL)	e-		e+e- LCs, DWFA	
BELLA (LBNL)	laser		e+e- LCs, LWFA	FEL, γ's, medical laser-gas
FACET (SLAC)	e-, e+		e+e- LCs, PWFA	
TTF (DESY)	e-		Initially – e+e- LC	FEL, SCRF technology
ASTA (Fermilab)	e-,p/ions, laser	Losses, beam dynamics, novel optics, space-charge compensation, collimation, diagnostics	e+e- LCs, e+ sources, LHC & upgrades, Muon Collider R&D	FEL, γ's, SCRF techn. dev. & test, material test



- **Variable energy from ~40 to ~900 MeV,**
- **High-repetition rate (1-ms trains):**
  - **Exploration of dynamical effects in beam-driven acceleration methods.**
- **L-band SCRF linac:**
  - **Very high power**
- **Photoinjector source:**
  - **low-emittance beam,**
- **Arbitrary emittance partition:**
  - **tailored current profiles.**

Advanced Superconducting Test Accelerator (ASTA)



<40 MeV

< 750 MeV

< 1 GeV

ASTA Program Proposal & Synergies

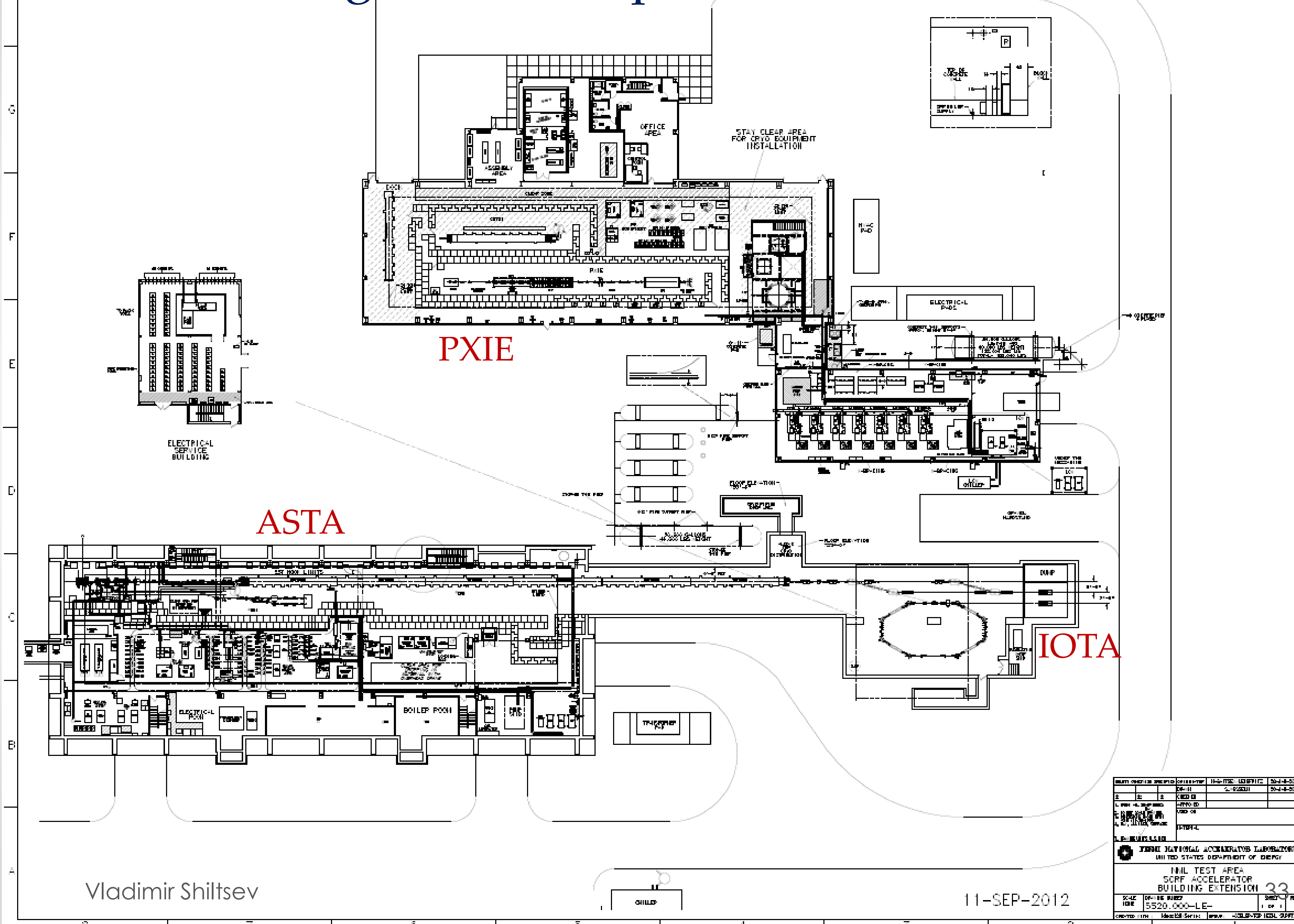
- **Users – Labs, Universities, SBIRs, Int'l:**
  - 21 proposals as of now
  - LBNL, Jlab, ORNL, LANL, NIU, IIT, JAI, DOD, Muons,Inc., Radiabeams, Tech-X, etc

Many $M's of investment from OHEP programs, projects, ARRA, State of Illinois

Synergies:

- **FNAL SRF Program:**
  - 1 to 3 SC RF 1.3 GHz cryomodules
- **A0 photoinjector:**
  - Expertise & hardware moved to NML
- **General Accelerator Development:**
  - HINS RFQ and H- source to move to NML
- **IARC:**
  - Facility to be open for industrial development, education

World-leading R&D Campus for future accelerators



IOTA: Integrable Optics Test Accelerator

Electron beam parameters

- Tkin = 40-180 MeV
- P = 40.5-150.5 MeV/c
- Beta = 1
- Gamma = 295
- Nominal magnetic rigidity = B rho = 0.5 Tm

Table 1: Summary the main parameters of IOTA

Parameter	Value
Nominal beam energy	150 MeV(γ=295)
Nominal beam intensity	1×10^9 (single bunch)
Circumference	38.7 m
Bending field	0.7 T
Beam pipe aperture	50 mm dia.
Maximum β-function	$3 \div 9$ m
Momentum compaction	$0.015 \div 0.1$
Betatron tune	$3.5 \div 7.2$
Natural chromaticity	$-5 \div -15$
Transv. emittance, rms	$0.02 \div 0.08$ μm
SR damping time	0.5s (5×10^6 turns)
RF V, f, harmonic	75 kV, 162.5 MHz, 21
Synchrotron tune	$0.005 \div 0.01$

- **Experiments with electrons :**
  - **Beam dynamics in integrable optics with non-linear magnets**
  - **Integrable dynamics with “electron lens(es)”**
  - **Proof-of-principle of “Optical Stochastic Cooling”**
    - **without an amplifier**
    - **with amplifiers**
  - **Electron quantum wavelength determination**
  - **other**

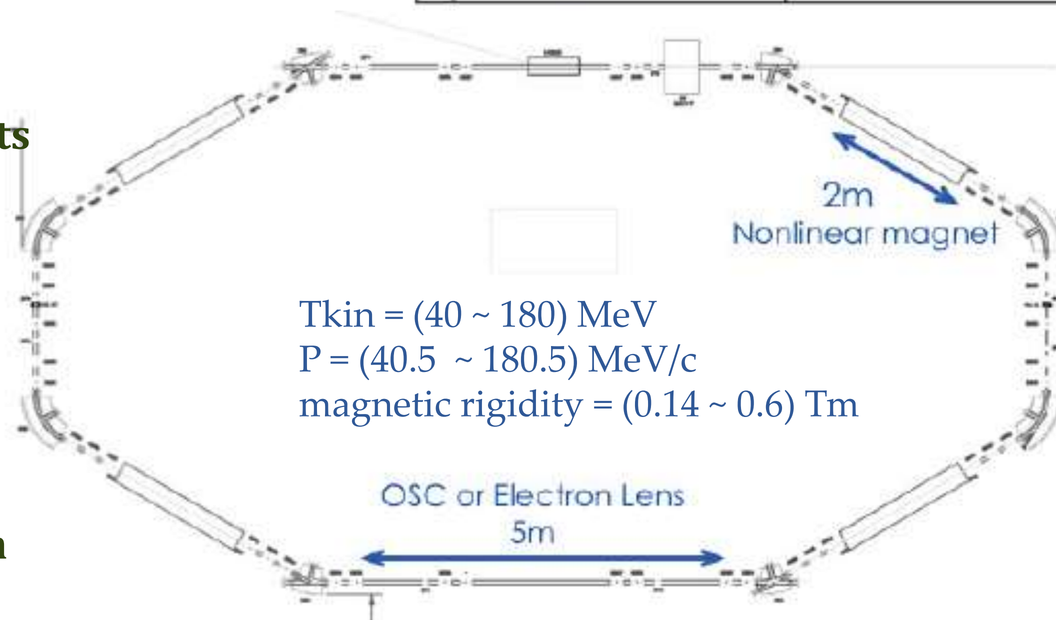


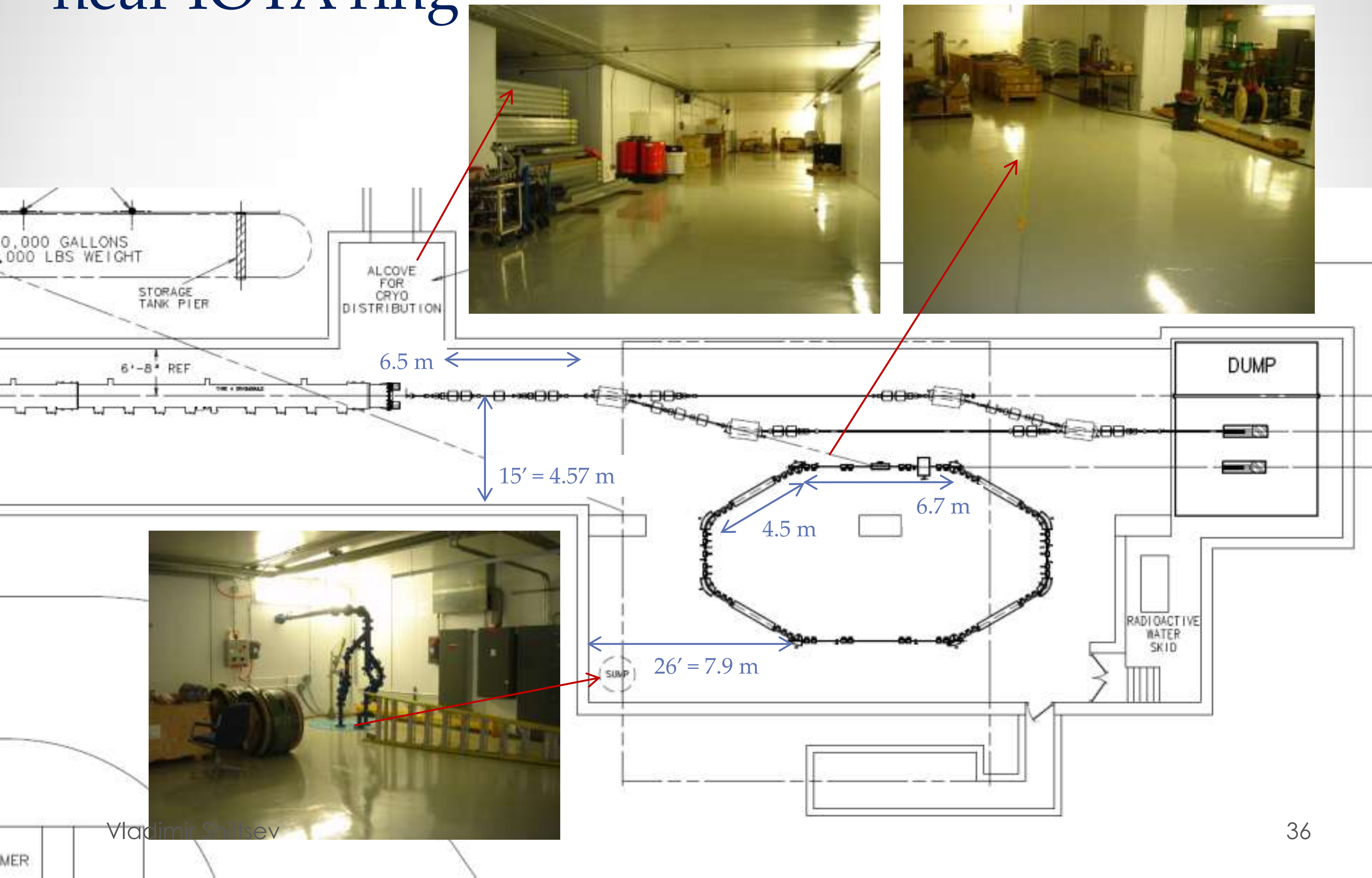
Figure 1: Layout of the IOTA ring.

Protons in IOTA (M.Chung, V.Shiltsev)

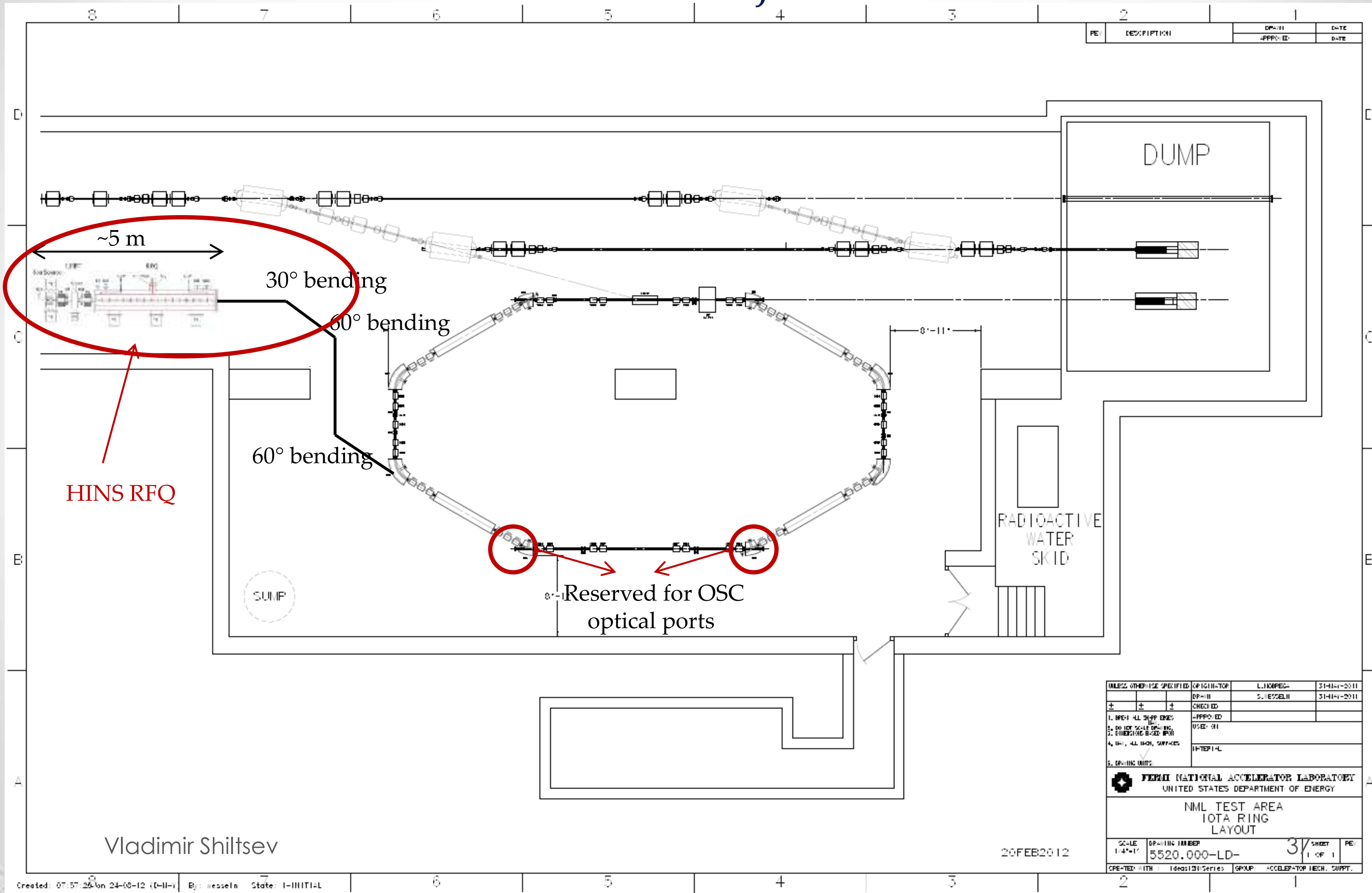
- **Re-use HINS RFQ &H- source**
- **Move them to ASTA**
- **Inject p's to IOTA via charge exchange injection (stripping)**
- **Will they fit in?**
  - **For relativistic electrons momentum $p=E/c$**
  - **For non-relativistic protons $E\_kin=p^2/2m$, so $p=(2m\ E\_kin)^{1/2}$**
- **E.g., 2.5 MeV protons have $p=(2\ \mathrm{1GeV}\ 2.5\ \mathrm{MeV})^{1/2} = 70\mathrm{MeV/c}$**
- **Perfect fit for IOTA optics which is set for p=40-150 MeV/c**

- **IOTA experiments with protons :**
  - **Beam dynamics of space-charge dominated beam in linear optics**
  - **Halo formation studies and diagnostics**
  - **Beam dynamics of space-charge dominated beam in non-linear integrable optics**
  - **Space-charge compensation with either "electron lens(es)" or with "electron columns"**
    - **Achieve dQ_sc ~1-3**
  - **Other tests (e.g., those planned for HINS)**

Existing HINS 2.5MeV H- RFQ to be installed near IOTA ring



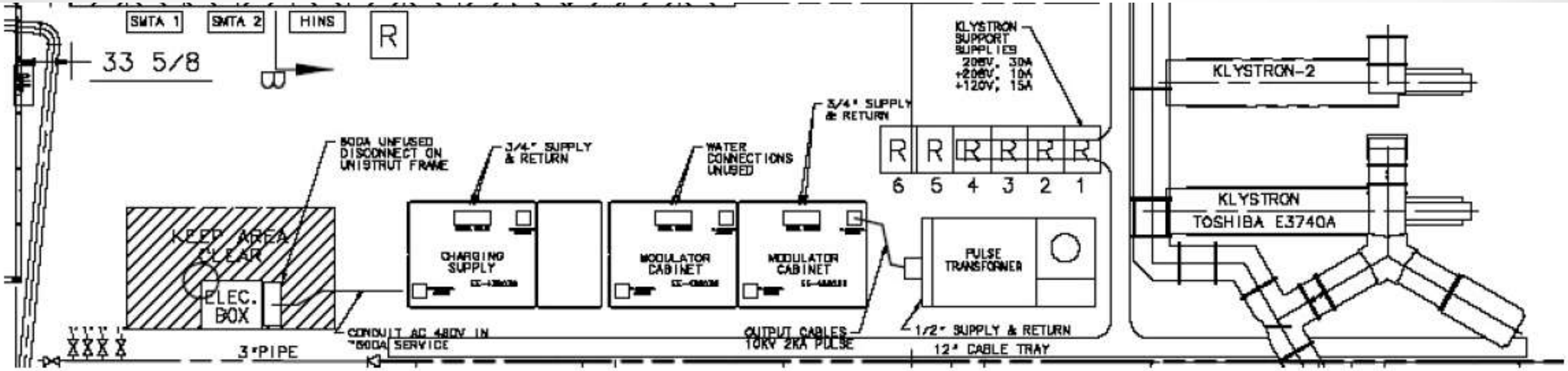
Possible configuration:
Counter-direction of electron injection



Vladimir Shiltsev

RF components

- 325 MHz Toshiba klystron
- 2.5 MeV long pulse RFQ
- etc




Charging supply


Circulator


Waveguide components

Beam components

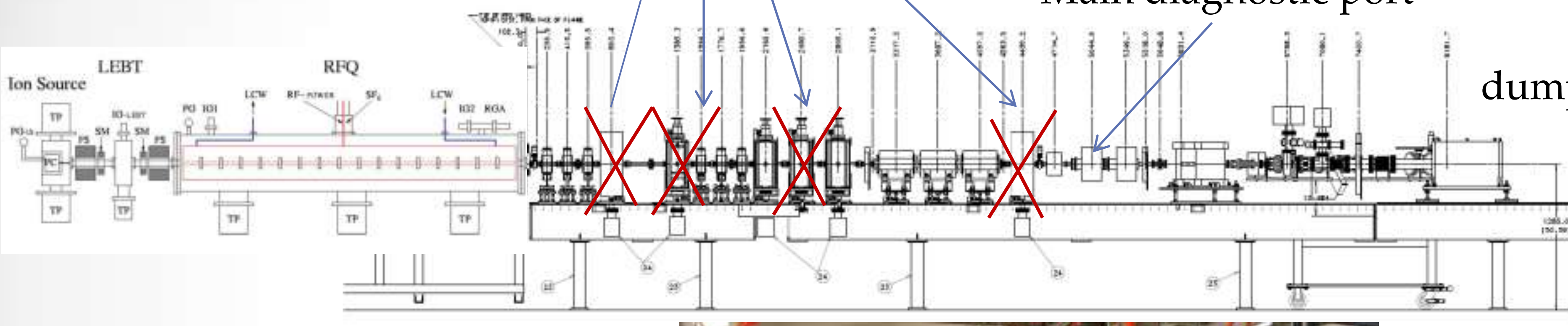
Maybe, no 6 cavity for ITOA injection

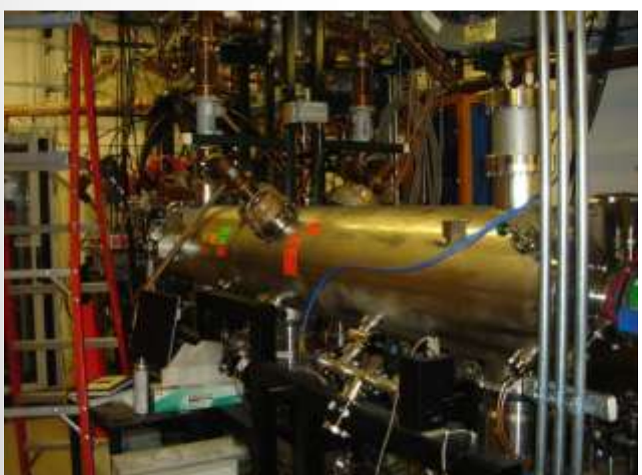
~ 4.7 m

~ 5.7 m

Main diagnostic port

dump





Proton beam parameters for IOTA:

- Tkin = 2.5 MeV
- P = 68.5 MeV/c
- Beta = 0.073
- Gamma = 1
- Nominal magnetic rigidity = B rho = 0.23 Tm

Estimated momentum spread

I (mA)	σ_x (mm)	$(\Delta p/p)_{rms}$ (%)
0	2.55	0.378
10	2.58	0.371
0	2.59	0.378
10	2.69	0.366

By Eliana GIANFELICE

HINS Beam Parameters

	Proposed	Actual	
Particle	H+ then H-	H+ then H-	
Nominal Bunch Frequency/Spacing	325 3.1	325 3.1	MHz nsec
Pulse Length	3 @ 2.5 Hz 1 @ 10 Hz	1 @ 0.2 Hz 0.1 @ 1 Hz	msec
Average Pulse Current	~ 20 (source)	~ 20 (H, 2H+, 3H+) ~8 (RFQ - H)	mA
Pulse Rep. Rate	2.5/10	0.2/1	Hz
Beam Energy	Up to 10	2.5 to 3.0	MeV

DITANET Workshop 2011

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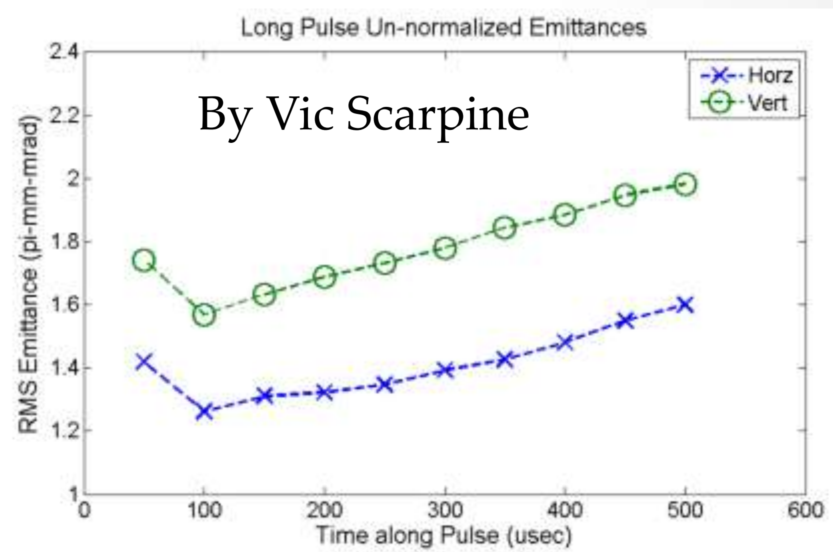
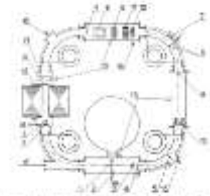


By Vic Scarpine

~2.0 pi-mm-mrad vertical
~1.6 pi-mm-mrad horizonal

IOTA proton-beam: better than Novosibirsk PSR



1.	Proton energy	1 MeV	2.5 MeV
2.	Field intensity in bending magnets	3500 G	7000 G
3.	Index of field decrease	0.2 to 0.7	
4.	Radius of rotation in magnets	42 cm	
5.	Length of the straight sections of an orbit	106 cm	
6.	Aperture of vacuum chambers in bending magnets	6 × 4 cm	5 cm
7.	Revolution frequency of protons in the storage ring	1.86 MHz	0.56 MHz
8.	Duration of injection pulse	up to 300 μsec	up to 1000 μsec
9.	Repetition frequency of injection pulse	0.2; 0.1 Hz	0.2; 1 Hz
10.	Injection current	up to 8 mA	up to 8 mA

HINS + IOTA

Injection parameters:

- Revolution time = C / (beta c) = 1.77 μsec
- Revolution frequency, frev = 0.56 MHz
- Pulse length = 500 μsec
- Number of turns = 282
- Injection current, Ip = 8 mA
- Particle per pulse, ppp = I x 500 μsec / e = 2.5 x 10^{13}
- Maximum stored protons, $N_{p,max}$ = 2.5 x 10^{13} (when no injection loss)
- Maximum ring current, Iring = $N_{p,max}$ x e x frev = 2.25 A
- Space-charge tune shift: $$|\Delta\nu_{sc}| = \frac{N_p r_0}{4\pi\beta^2\gamma^3\varepsilon_{rms}} = 1 \sim 282 \text{ (roughly 1 for each injection turn)}$$

Space Charge Idea #3 : Integrable Optics (Danilov since ~2000, + Nagaitsev 2010)

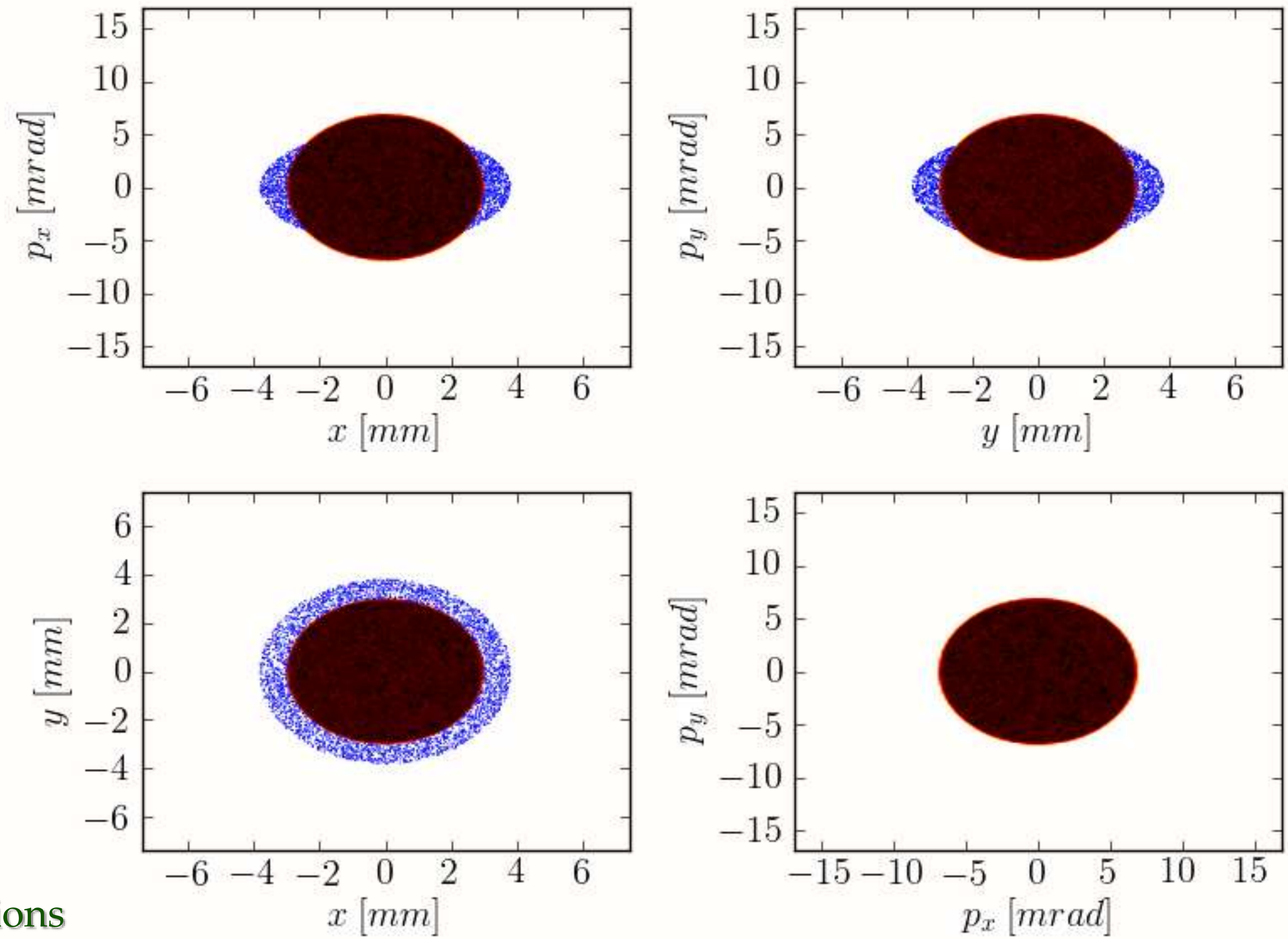
- **Employment of special nonlinear fields to stabilize particle's motion:**
  - **Make motion limited and long-term stable (usually involves additional "integrals of motion")**
  - **Can be Laplacian (with magnets, no extra charge density involved)**
  - **Or non-Laplacian (with externally created charge – e.g. special e-lens *E(r) ~r/(1+r^2)***
  - **(That's what IOTA is for – test with electrons)**
  - **Should be directly applicable to protons with SC**

Proton Space Charge in Linear Optics Ring

System: linear FOFO; 100 A; linear KV w/ mismatch

Result: quickly drives test-particles into the halo

dQ_sc ~ 0.7



Tech-X simulations

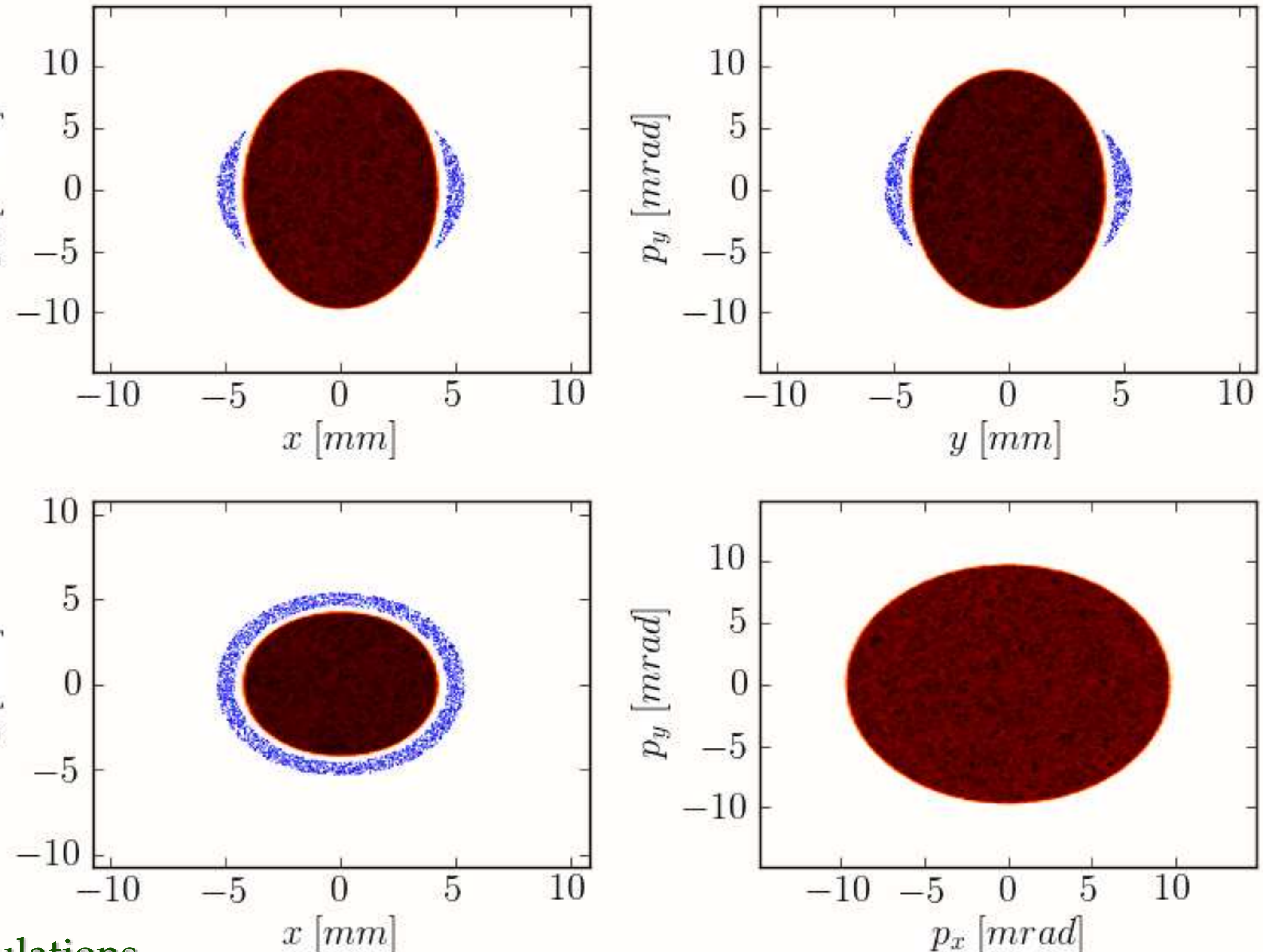
500 passes; beam core (red contours) is mismatched; halo (blue dots) has 100x lower density

Proton Space Charge in Integrable Optics

System: octupoles; 100 A; generalized KV w/ mismatch

Result: nonlinear decoherence suppresses halo

dQ_sc ~ 0.7



Tech-X simulations

500 passes; beam core (red contours) is mismatched; halo (blue dots) has 100x lower density

IOTA : Unique opportunity to make impact for Intensity Frontier

- **Experiments with 50-150 MeV electrons:**
  - Integrable Optics test with non-linear magnets
  - Integrable Optics test with e-lens(es)
  - Optical Stochastic Cooling Test
  - Electron quantum wavefunction size, etc
- **Experiments with 2.5 MeV H- and protons :**
  - H- halo and stripping
  - SC modes and dynamics in the ring / integrable
  - SC compensation with e-columns or/and e-lenses
  - Beam / halo diagnostics , etc

Summary

- **Space Charge effects were addressed by our community for some 5 decades – lot of progress**
- **Several ideas of SC-compensation proposed and some explored:**
  - **Issues: stability or range of compensation**
- **Recent proposal of SCC with electron lenses or with (cheaper) e-column offers some advantages:**
  - **Stability of e-p system, good results in simulations**
- **Experimental test of the SCC with e-lenses/columns /integrable optics are very desired → are being planned:**
  - **At IOTA Ring at the Fermilab's ASTA facility**

That can open a whole new world for high intensity proton accelerators.

You are very welcome to join!

Acknowledgements

- **Input from:**
  - Yu. Alexahin
  - W. Foster
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  - V. Dudnikov
  - V. Danilov
  - A. Valishev
  - M. Chung
  - S. Nagaitsev
  - G. Stancari
  - A. Kabantsev